Reports of the Department of Geodetic Science

Report No. 70

THE DETERMINATION AND DISTRIBUTION OF PRECISE TIME

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 6.00

Microfiche (MF) 1.25

ff 653 July 65

by
Hans D. Preuss

Prepared for
NATIONAL AERONAUTICS and SPACE ADMINISTRATION
WASHINGTON, D.C.

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION
Columbus, Ohio 43212

April, 1966

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OSURF Project No. 1997

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PREFACE

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Precise time, distributed by means of radio broadcasts, is required for two similar geodetic tasks: astronomic position determination; and observations of artificial satellites for geodetic purposes.

The aim of this report is to assimilate under one cover the various phases of the determination and distribution of precise time.

The determination of time has become a specialized field of astronomy and is presented in Chapter II. Timekeeping and the basis of constant frequency is discussed in Chapter III. Chapter IV deals with variations in the time systems which are connected to the rotation of the Earth, and with the corrections that have to be applied to observed time. The distribution of precise time through radio broadcasts is presented in Chapter V. Finally, the manner in which the geodesist ought to use distributed time and the corrections that have to be applied to received radio time signals are discussed in Chapter VI.

Although the discussion leads into non-geodetic fields and theoretical foundations have to be neglected for want of space, it is hoped that this study of the present state of the art will provide some understanding of the basis of precise time and its distribution.

The report was prepared under the supervision of Prof. Ivan I. Mueller. The execution of this research is under the technical direction of the Director, Physics and Astronomy Programs, and of the Project Manager of the National Geodetic Satellite Program, both at NASA Headquarters, Washington, D.C. The contract is administered by the office of Grants and Research Contracts, Office of Space Science and Applications, NASA, Washington, D.C.

Author

ACKNOWLEDGEMENTS

The writer gratefully acknowledges the help, guidance and encouragement received from Professor Ivan I. Mueller, not only while preparing this paper but during his entire period of study at this university.

Further, gratitude is extended to Dr. William Markowitz, Director, U. S. Naval Observatory Time Service, for a stimulating discussion on the subject of this paper in September 1965. Several other individuals have contributed greatly. Special thanks go to Mr. John Badekas for his valuable translations of French publications, and to Mrs. Jan weller for typing this report.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd.)

TABLE OF CONTENTS (cont'd.)

TABLE OF CONTENTS (cont'd.)

TABLE OF CONTENTS (cont'd.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd.)

LIST OF TABLES

LIST OF TABLES

NOTATION INDEX

The following is a list of abbreviations and symbols used throughout the text with the same meaning.

A	astronomic azimuth
A.1	atomic time of the USNO
A3	atomic time of the BIH
AST	apparent (true) sidereal time
AT	atomic time
BIH	Bureau International de l'Heure, Paris, France
Cs	caesium
Cs(H12)	atomic time of the RGO
D	distance
ET	ephemeris time
Eq. E	equation of the equinox
FK4	Fourth Fundamental Catalogue
G	prefix refers to Greenwich
Hg	mercury
Hz	Hertz, 1 Hz = 1 cycle per second
IAU	International Astronomical Union
ILS	International Latitude Service
IPMS	International Polar Motion Service
LSRH	Laboratoire Suisse de Recherches Horlogères, Neuchâtel, Switzerland
M	prefix denotes mega = 10^6
MST	mean sidereal time
MT	mean time

NOTATION INDEX (cont'd.)

NBS	U. S. National Bureau of Standards, Boulder Colorado
NBS-A	atomic time of the NBS
NPL	National Physical Laboratory, Teddington, Great Britain
P	polar motion correction to time
PZT	photographic zenith tube
Rb	rubidium
RGO	Royal Greenwich Observatory, Herstmonceux, Great Britain
RLS	Rapid Latitude Service
S	seasonal variation correction to time
T	epoch of time
TA.1	atomic time of the LSRH
UT	universal time
UTO	observed universal time
UT1	UTO corrected for polar motion
UT2	UT1 corrected for seasonal variation
h	hour angle
h	superscript denotes hour
k	prefix denotes kilo = 10^3
m	superscript denotes minute
m	prefix denotes milli = 10^{-3}
s	superscript denotes second
s	scale factor
t	epoch of time

NOTATION INDEX (cont'd.)

Δ	prefix denotes correction
$\Delta\lambda$	correction to time for polar motion
Δs	correction to time for seasonal variation in the Earth rotation speed
Λ	astronomic longitude, positive to the east
Σ	summation
Φ	astronomic latitude, positive to the north
α	right ascension
Υ	vernal equinox
δ	declination
ζ	north zenith distance
μ	prefix designates micro = 10^{-6}

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I. DEFINITION OF TIME SYSTEMS

1.1 Introduction

Before commencing with the discussion of time systems it is necessary to distinguish between two main aspects of time: the epoch (time instant) and the time interval. The epoch defines the instant of occurrence of a phenomenon, or the instant of an observation. The time interval defines the time elapsed between any two epochs, measured in some scale of time, which defines a specific time system. The unit of time, in any system, is always a time interval.

The fundamental requirement that must be met by any time system is an established relationship between the adopted scale of time (usually in the form of years, months, days, hours, minutes, seconds, and fractions of seconds) and a physical phenomenon which is observable and countable, or continuous and measurable, or both. Furthermore, the phenomenon on which a specific time system is based must be free of short periodic variations to permit interpolation and extrapolation by means of man-made time keeping devices [Mueller, 1964c].

Scientific, technical, and civil demands on a practical time system do agree as far as the above stated requirements are concerned. They differ however on questions as to the scale of time suitable for specific purposes. Four basic time systems, each one associated with a particular phenomenon, are in general use today. These are:

sidereal time and universal time, based on the rotation of the Earth;

ephemeris time, based on the motions of the Earth, Moon and planets in the solar system;

atomic time, based on the frequency of oscillation of atoms.

Sidereal time and universal time are equivalent forms of time in as much as the two are related by rigorous formulae. Ephemeris and atomic time are independent systems. Their relationship to each other and to universal or sidereal time has to be established through observations empirically.

Since the sidereal, universal and ephemeris time systems are well defined in the "Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac" [Nautical Almanac Offices, 1961] and elsewhere, only the definition of the atomic time system is given here. A graphical representation of the other time systems is shown in Figure 1.1. For the sake of completeness the true solar time system is also shown in Figure 1.1, although it is neither distributed nor used in the determination of precise time.

The expression "mean solar time" is still frequently used in the literature in lieu of universal time. Furthermore, the term universal time has been reserved to designate a particular epoch referred to the Greenwich meridian. To avoid confusion the following terminology will be used in this text: <u>universal time</u>, UT, is an epoch in the universal time system referred to the Greenwich or zero meridian; <u>mean time</u>, MT, is an epoch in the universal time system referred to any meridian other than Greenwich. A time interval in the universal time system will be called <u>mean time interval</u>.

Universal time is non-uniform, owing to variations of the local meridian due to polar motion (see Section 4.2) and variations in the rotation speed of the Earth (see Section 4.3). There are three different types of universal time. These are:

> UT0 is the epoch of universal time as determined from star observations;
>
> UT1 is UT0 corrected for polar motion;

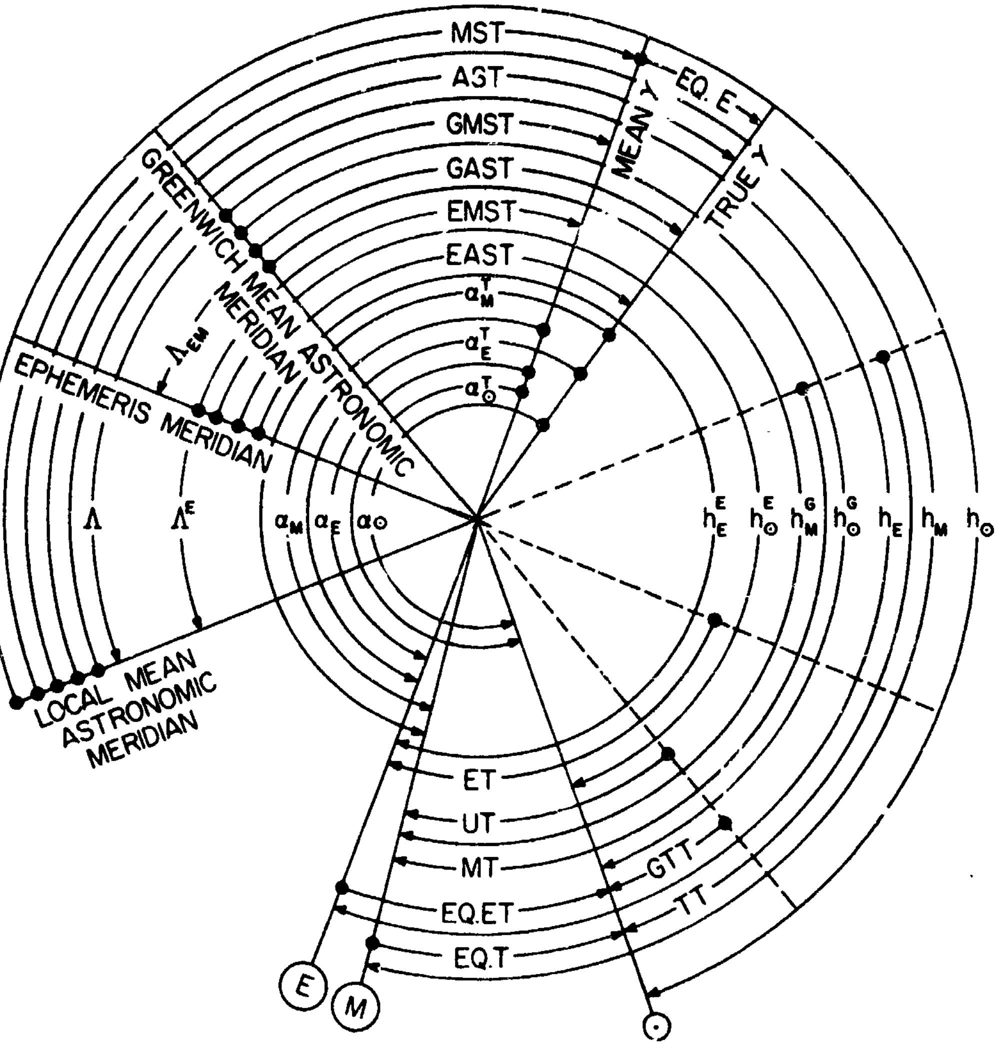


Figure 1.1: Rotational and ephemeris time systems in the equatorial plane. From [Mueller and Rockie, in Press].

Symbols	
AST	apparent sidereal time
MST	mean sidereal time
ET	ephemeris time
MT	mean time
UT	universal time
TT	true solar time
Eq.T	equation of time
Eq.E	equation of equinoxes
Eq.ET	equation of ephemeris time
Λ	longitude
Λ_{EM}	longitude of ephemeris meridian
α	mean right ascension
α^T	true right ascension
γ	vernal equinox

Symbols	
h	hour angle
E	ephemeris
G	Greenwich
^{G}	refers to Greenwich meridian
^{E}	superscript refers to ephemeris meridian
$\odot$	refers to true Sun
$_M$	refers to fictitious Sun
$_E$	subscript refers to fictitious mean Sun
⊙	true Sun
Ⓜ	fictitious Sun
Ⓔ	fictitious mean Sun

UT2 is UT1 corrected for seasonal variation in the rotation speed of the Earth.

UT2, however, is still non-uniform, owing mainly to uncompensated variations in the rate of rotation of the Earth.

1.2 Atomic Time

Atomic time, AT, is a uniform time system based on the operation of so-called atomic clocks. An atomic clock is formed by associating a precise quartz crystal clock with an atomic frequency standard. Clocks and frequency standards are described in Chapter III.

For the time being it shall suffice to say that workable atomic clocks are usually based on the resonant frequency of the caesium-133 atom.

Atomic time is appropriately used where the uniformity of the time interval is of importance, such as in timing of experiments in physics. It may be used advantageously in lieu of ephemeris time in connection with astronomic or satellite observations, e.g., when an artificial satellite ephemeris has to be established. The fact that the oscillation frequency of the caesium atom has been determined in terms of ephemeris time makes the substitution of AT for ET possible (see Section 1.22).

There are several atomic time scales in existence. Those which are frequently mentioned in the literature are the following.

A.1: is an atomic scale of time determined and adopted by the U. S. Naval Observatory, Washington, D. C. (USNO). It is based on the operation of 8 caesium beam frequency standards located as follows: USNO; U. S. Naval Research Laboratories, Washington, D. C.; USNO Substation, Richmond, Florida; U. S. National Bureau of Standards, Boulder, Colorado (NBS);

Cruft Laboratory, Cambridge, Massachusetts; National Physical Laboratory, Teddington, Great Britain (NPL); Laboratoire Suisse de Recherches Horlogères, Neuchâtel, Switzerland (LSRH); and Postes et Télégraphes, Bagneux, France [Markowitz, 1962a, p. 11].

NBS-A: is an atomic time scale maintained by the NBS. It is based on the operation of two caesium beam standards designated NBS-I and NBS-II, respectively [Mockler, 1964, p. 524].

A3: is the atomic time scale adopted by the Bureau International de l'Heure, Paris, France (BIH). It is based on the caesium beams operated at the NBS, the NPL, and the LSRH [BIH, 1965, p. 13].

TA.1: is the atomic time scale determined at the LSRH. It is based on the operation of a caesium beam and an ammonia Maser frequency standard [Morgan et al., 1965, p. 507].

Cs(H12): is the atomic time scale determined at the Royal Greenwich Observatory (RGO), located at Herstmonceux, Great Britain. It is based on the caesium beam operated at the NPL [Royal Greenwich Observatory, 1965, p. B262].

The formation of atomic scales of time may be understood more easily after reading Sections 3.2, 3.43, and 5.32.

1.21 The atomic time epoch

The fundamental epoch of atomic time depends on the initial reading of an atomic clock and is, therefore, different for each of the systems mentioned above.

The adopted initial epoch for A.1, for instance, is $0^h0^m0^s$ UT2 on January 1, 1958, at which instant A.1 was $0^h0^m0^s$ [Markowitz, p. 95].

The adopted initial epoch of A3, on the other hand, has been chosen such that the difference UT2 - A3 = $0^h0^m0^s$, which was the case at 20^h UT2, January 1, 1958 [BIH, 1965, p. 3].

Other atomic time systems will have different initial epochs. For the NBS-A system, for instance, the initial epoch was chosen to coincide with the A.1 system. The correspondence has an uncertainty of about ±1 millisecond. In addition to this, the systems A.1 and NBS-A seem to diverge at a rate of 2 x 10^{-11} sec/sec [Mockler, 1964, p. 524]. The same magnitude of divergence exists between the systems NBS-A and TA.1 [Bonanomi et al., 1964]. The difference between the epoch of A3 and A.1 is about $-0^s.035$ [Stoyko, A., 1964c, p. 76].

Concerning the epoch of atomic time, we note that there exists no requirement for a definite epoch; atomic time is a measure of interval.

1.22 The atomic time interval

The fundamental unit of time, the second, was defined by the XIIth general assembly on weights and Measures at Paris in October, 1964. The exact wording of the new definition is: "The standard to be employed is the transition between two hyperfine levels F = 4, m_F = 0 and F = 3, m_F = 0 of the fundamental state $^2S_{1/2}$ of the atom of caesium-133 undisturbed by external fields and the value 9 192 631 770 Hertz is assigned", where F designates a particular energy state of the atoms, and m_F - 0 stands for zero magnetic field [Hewlett-Packard, 1965, p. AII-2].

The above definition means that the second is expressed in terms of the frequency of the caesium atom (see Section 3.21). The new definition is in as close agreement as is experimentally possible, with the 1956 definition of the second in terms of ephemeris time (see [Nautical Almanac Offices, 1961, p. 70]).

From a previous experiment, conducted jointly by the USNO and the NPL, it was found that the frequency of caesium-133 at zero magnetic field at 1957.0 was 9 192 631 770 ± 20 cycles per second of ephemeris time. The epoch of the agreement is stated because the atomic and gravitational time scales may diverge due to cosmic causes [Markowitz, p. 94].

It should be pointed out that the relationship between the atomic and ephemeris second is liable to change if the gravitational theory of the Sun should be revised in the future. The magnitude of the possible changes cannot be forecast with certainty [Markowitz, 1962b, p. 241].

II. OBSERVATORY DETERMINATION OF THE EPOCH OF TIME

2.1 Introduction

In the following discussion of the practical determination of the epoch of time we may conveniently subdivide the topic in the determination of rotational time, i.e., sidereal and universal time, and the determination of ephemeris time. Although the former section involves variations in the rate of the Earth's rotation and the variation of the meridian due to motion of the pole, these phenomena are treated in Chapter IV.

The determination of time has become a highly specialized branch of astronomy and is usually executed by national observatories. The basic requirements concerning time determination, e.g., star catalogues to be used, have been standardized by the International Astronomical Union (IAU). The BIH has been established to coordinate and compare the results of various time determinations.

It is not possible here to treat all methods and instruments in use but principles only. The principle of the determination of rotational time with the photographic zenith tube (PZT) and the Danjon impersonal prismatic astrolabe will be shown. The discussion of the determination of ephemeris time will be restricted to the dual-rate Moon camera method.

2.2 The Determination of the Universal Time Epoch

As pointed out in the foregoing chapter universal and sidereal time are related by formulae. Since the fictitious Sun, whose Greenwich hour angle defines the epoch of UT is not observable, universal time is determined in practice through the intermediary of sidereal time. The determination involves principally three steps:

(1) stars of known position are observed to determine local mean sidereal time, MST;

(2) MST is converted to MT;

(3) the conventional longitude difference between the place of determination and Greenwich is added to convert MT to UT.

Step (1) is obviously a critical one since the accuracy of star observations is limited by instrumental and observational factors, as well as by the accuracy of star catalogues. Step (2) involves the theory of motion of the fictitious Sun, and step (3) requires a knowledge of the precise longitude of the place of observation.

2.21 Meridian observations with the PZT

The historical development of the PZT from Airy's reflex zenith tube is given in [Markowitz, 1960a, pp. 92-100]. The structural design and operation of the PZT will be briefly described, based on the above publication. A full view of the PZT is shown in Figure 2.1.

The PZT is mounted in a vertical position and has a field of 27′ to 34′. Thus, only stars which transit near the zenith, where atmospheric refraction will be at a minimum, can be observed. The light rays from the star pass through the lens, are reflected by a basin of mercury at the bottom of the tube and come to a focus about 1 cm below the inner face of the lens.

A lens has two nodal points associated with it. A light ray which enters the lens at one nodal point leaves it at the second nodal point in a parallel direction. Normally, the nodal points lie within the lens. It is however, possible to design a lens system so that both nodal points are exterior to the lens.

Figure 2.1: The photographic zenith tube, PZT, of the U.S. Naval Observatory. The mercury basin is seen at the bottom of the photograph, the motor driving the plate carriage is seen at the top (left) of the telescope tube. (Official U.S. Navy photograph.)

The optical system of the PZT is designed such that the inner nodal point lies in the focal plane. The photographic plate is located at the focal plane and is rigidly connected to the lens cell. After reflection from the mercury surface, a light ray from the zenith will form an image on the plate which will coincide with the inner nodal point. Neither tilting nor horizontal translation of the lens cell will alter the position of the zenith on the plate. The position of the image of a star which is not at the zenith will not be sensibly displaced by these motions. A rotation of the lens cell by 180°, however, displaces the image of a star symmetrically about the zenith.

The photographic plate is mounted in a carriage which is driven by a motor synchronized to track the stars by moving the plate carriage in an east-west direction. In addition, the carriage and lens cell can be rotated 180° by a motor driven rotary between exposures. The motion of the carriage during exposure triggers timing pulses which are recorded with respect to a crystal clock.

Four exposures of 20 seconds are made of each star in alternating rotary positions, two before and two after transit. The interval between the mean exposure times is 30 seconds, exactly.

Each exposure is started with the center of the plate 10^s west of the meridian. At the end of the exposure it is 10^s east. Reversal of the rotary brings the center of the plate back to 10^s west. If the motor driving the plate carriage is east, the plate moves towards the motor, if it is west, the plate moves away from the motor.

The images of a star appear on the PZT plate as shown in Figure 2.2.

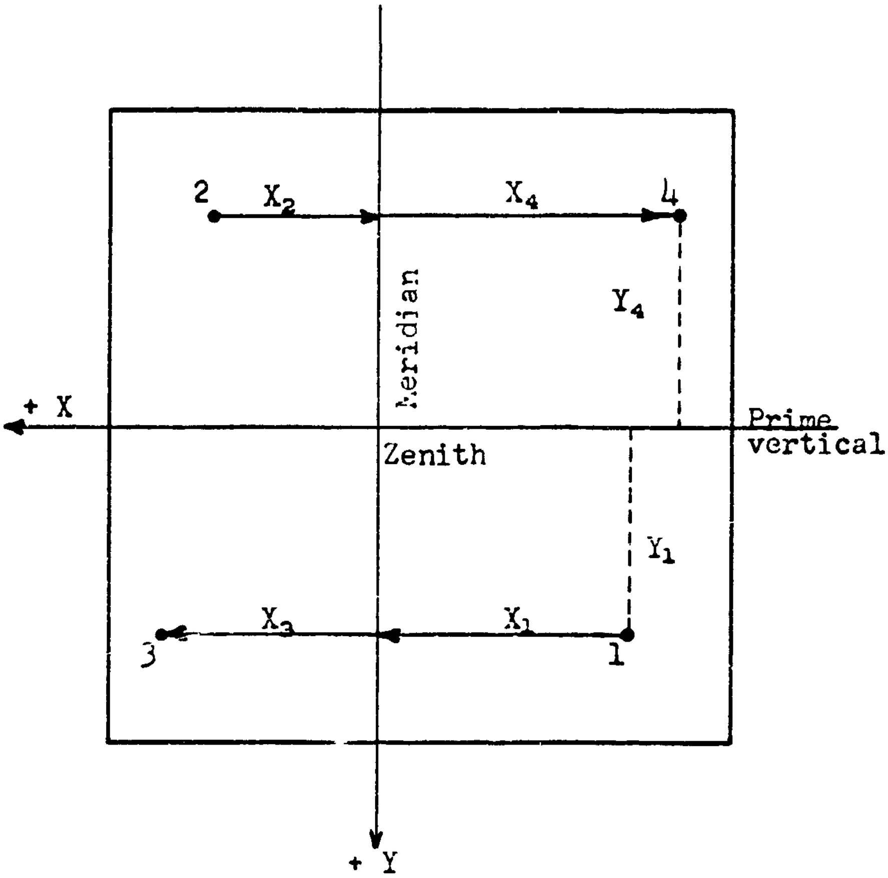


Figure 2.2: Appearance of the images of a star on the PZT plate. The arrows indicate the direction of the star's motion with respect to the meridian. The numbers indicate the sequence of exposures.

If the exposures would be symmetrical with respect to time of meridian passage, the images would form a rectangle. The images of the zenith and meridian are fixed with respect to the lens cell, but their positions on the plate change.

The relationship between the time of transit and the position of the images on the plate can be visualized geometrically. To do this we assume that the star moves up to the meridian at a uniform rate and then instantly reverses its motion and moves in the opposite direction at the same rate.

Let the mean epochs of the timing pulses be t_1, t_2, t_3, t_4 for the four exposures. An interval timer measures the interval between the impulse from the camera shutter to the nearest second of the clock. Let these intervals be p and q for the motor position west and east, respectively. If we denote the clock second following t_1 by T we have, starting with motor west,

$$t_1 = T - p, \qquad t_3 = T + 60^s - p,$$
$$t_2 = T + 30^s - q, \qquad t_4 = T + 90^s - q, \tag{2.1}$$

The mean time of the sequence is $1/2\ (t_1 + t_4)$, or

$$t_0 = T + 45^s - 1/2\ (p + q). \tag{2.2}$$

Subtracting Equations (2.1) from (2.2) we get

$$t_1 = t_0 - 45^s - s, \qquad t_3 = t_0 + 15^s - s,$$
$$t_2 = t_0 - 15^s + s, \qquad t_4 = t_0 + 45^s + s, \tag{2.3}$$

where $s = 1/2\ (p-q)$. Starting with motor east, s has the opposite sign. The hour angles of the star may be expressed by Equation (2.3) by replacing $t_1, \ldots, t_4$ by $h_1, \ldots, h_4$ and t_0 by h_0.

By definition, the hour angle, h, of a star is

$$h = AST - \alpha, \tag{2.4}$$

where h is positive to the west, AST is the local apparent (true) sidereal time, and α is the known apparent right ascension of the star.

If we let $AST = t_0 + \Delta t$, where Δt is a correction to the observatory clock, Equation (2.4) becomes

$$h_0 = t_0 + \Delta t - \alpha, \tag{2.5}$$

or

$$\Delta t = h_0 + \alpha - t_0 = AST - t_0,$$

which gives the correction to the observatory clock and constitutes the result of the time observation.

To determine h_0 from measurements on the photographic plate several reduction techniques are in use. The principle of reduction given below is adapted from [Tanner, 1955, pp. 345-347].

Imagine a plane tangent to the celestial sphere at the zenith. In this plane a rectangular coordinate system with origin at the zenith is positioned. The positive x-axis is directed to the east, the positive y-axis towards the south.

It can be shown that the rectangular coordinates of a star in seconds of arc are given by

$$\begin{aligned} x &= -\,15h\cos\delta \\ y &= -\,(\zeta' + kh^2), \end{aligned} \qquad (2.6)$$

where h is the hour angle in seconds of time, δ is the star's declination, ζ' its north zenith distance in seconds of arc, and k is a correction for the curvature of the star's path.

The telescope projects this coordinate system into the focal plane. A second coordinate system, XY, is assumed, in the photographic plate, to coincide with the xy system at time t_1 or t_3, i.e., when the motor is west.

Let the plate coordinates of the star's images at times t_1 through t_4 be X_1, X_2, X_3, X_4 and Y_1, Y_2, Y_3, Y_4. Then we have the following correspondence:

$$\begin{aligned} X_1 &= x_1 & Y_1 &= y_1 \\ X_2 &= -x_2 & Y_2 &= -y_2 \\ X_3 &= x_3 & Y_3 &= y_3 \\ X_4 &= -x_4 & Y_4 &= -y_4 \end{aligned} \qquad (2.7)$$

The scale of the plate is found from the X distances between images 1 and 3 and 2 and 4 in the plate and the corresponding time interval of 60^s exactly. Substituting h's for t's in Equation (2.3) and using Equation (2.6) we get

$$X_1 - X_2 - X_3 + X_4 = -\,15\,(h_1 + h_2 - h_3 - h_4)\cos\delta = 1800\cos\delta. \qquad (2.8)$$

When δ is known, this gives the scale of the plate in seconds of arc per revolution of the micrometer head of the measuring engine used to evaluate the photographic record. Let the scale factor be s.

The sum 1/4 $(X_1 - X_4 + X_3 - X_2)$ is equal to 1/4 $(x_1 + x_2 + x_3 + x_4)$, which, substituted into Equation (2.6) gives

$$s(X_1 - X_4 + X_3 - X_2) = -60\ h_0 \cos\delta . \tag{2.9}$$

Thus,

$$h_0 = \frac{(-X_1 + X_2 - X_3 + X_4)s}{60 \cos\delta} . \tag{2.10}$$

With h_0 known from Equation (2.10), the clock correction given by Equation (2.5) can be determined, or AST can be calculated from Equation (2.4).

PZT observations yield also the latitude of the observing station. The astronomic latitude, Φ , is given by

$$\Phi = \delta - \zeta , \tag{2.11}$$

where ζ is the north zenith distance of a star when it is on the meridian.

The observed double zenith distance is the distance between images 1 and 4, or 2 and 3, measured in the plate perpendicular to the prime vertical. We have from (2.7),

$$(Y_1 - Y_2 + Y_3 - Y_4) = (y_1 + y_2 + y_3 + y_4).$$

Substitution in Equation (2.6) yields

$$s(Y_1 - Y_2 + Y_3 - Y_4) = -4\zeta' + kh_0^2, \tag{2.12}$$

where ζ' is the observed zenith distance.

The difference $\zeta - \zeta'$ is the reduction of the observed zenith distance to the meridian, given with sufficient accuracy by

$$\zeta - \zeta' = -1/4(15^2\ h_0^2 \sin 2\delta \sin 1''). \tag{2.13}$$

The above is an idealized reduction method. In practice consideration must be given to the coordinate system of the measuring engine, focal length of the PZT, etc. Diurnal aberration must also be considered in the reduction. Corrections for refraction need not be applied because it is taken care of in the determination of the scale factor.

Usually, two scale factors are determined. One is used in the time, the other in the latitude determination. For details on practical reduction techniques the reader is referred to [Thomas, 1964], [Tanner, 1955 pp. 345-350], and [Takagi, 1961, pp. 137-149].

From Equations (2.5) and (2.11) it is clear that the coordinates of the stars, right ascension and declination, are needed for time and latitude observations, respectively.

The catalogue of star positions used in the PZT reductions is based as a whole on a fundamental system, such as the FK4. Internally, however, the positions are determined from the PZT observations themselves. The PZT catalogue is therefore free of accidental errors in the fundamental catalogue. For details the reader is referred to [Markowitz, 1960a].

2.211 Errors in the PZT observations

The principal sources of errors in the PZT time observations are:

a.) long and short period refraction anomalies

b.) errors in adopted star position

c.) plate measurement

d.) film distortion

e.) tilt of mercury surface

For the year May 1954 - May 1955 an extensive error analysis was made from the PZT observations at Washington and at Richmond. The probable errors determined from observations with the Washington PZT's are given in Table 2.1 below, taken from [Markowitz, 1960a, p. 107].

Table 2.1

Probable errors of PZT observations at Washington

	PZT No. 1		PZT No. 3	
	Time	Latitude	Time	Latitude
One star	$\pm 0^s.008$	$\pm 0''.125$	$\pm 0^s.007$	$\pm 0''.106$
One night, accidental	± 0.002	± 0.035	± 0.002	± 0.028
One night, systematic	± 0.003	± 0.041	± 0.003	± 0.047
One night, total	± 0.004	± 0.054	± 0.003	± 0.055

In summary Markowitz states that the probable error of one night of PZT observations at Washington or Richmond is $\pm 0^s.0045$ in time and $\pm 0''.055$ in latitude.

2.22 Extra-meridian observations with the Danjon impersonal prismatic astrolabe

The impersonal prismatic astrolabe, although entirely different in design from the PZT, yields similar results: time, latitude, and star positions. For the historical development of the instrument the reader is referred to [Danjon, 1960, pp. 115-121]. The structural design and method of operation of the simple astrolabe is briefly the following.

An equilateral glass prism, hereafter called main prism, is mounted in front of a horizontal telescope in such a way that its edges are horizontal and one face is vertical (Figure 2.3). A light beam from a star entering the main prism at a is reflected and emerges at b from the main prism and passes through the lens. Another beam enters the main prism at c, after it has been reflected by a mercury surface, is reflected and leaves the main prism at d and passes through the lens. In the eyepiece two images of the star are seen which appear to move along nearly the same vertical in opposite directions.

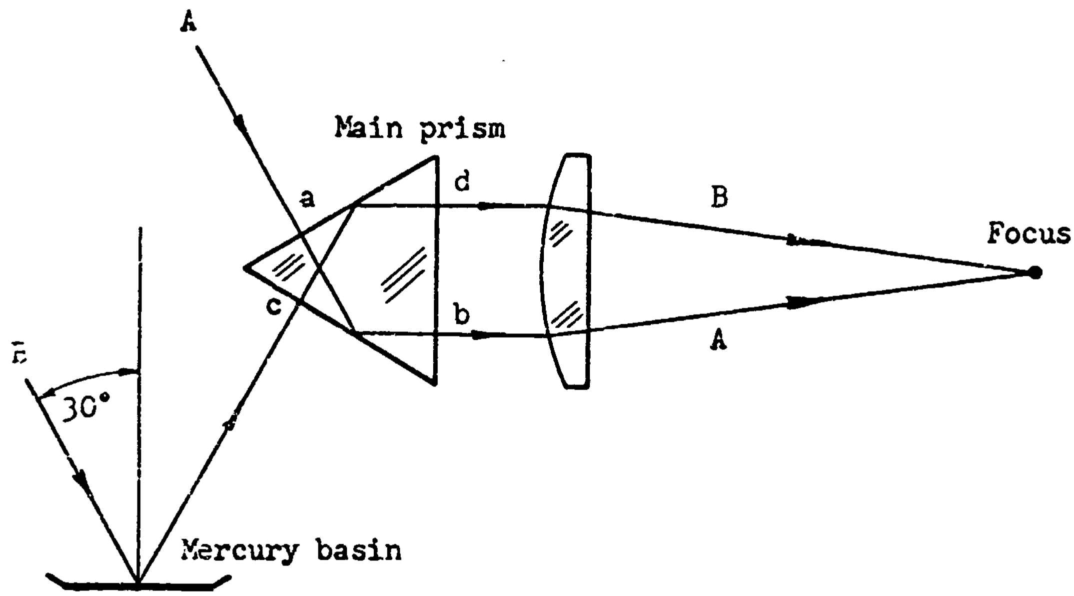


Figure 2.3: The optical principle of the simple astrolabe.

The two images coincide when the star's zenith distance is exactly 30°, provided the main prism angle is exactly 60° (other types of astrolabes employ 45° main prisms). The instant of coincidence of the two images with respect to a clock is recorded. Since the main prism angle is not precisely 60°, three unknown have to be determined, namely, corrections to the clock, latitude, and zenith distances. We will see later that a minimum of three observations in different azimuths are required to solve for the unknowns. Plotting position lines yields a graphical solution. For accurate work a least square adjustment is performed.

Just in front of the focus of the impersonal astrolabe (built by Societe Optique et Précision de Levallois (OPL) France) a double Wollaston prism has been placed which has the property of splitting the rays A and B in such a manner that two diverging and two parallel rays emerge (Fig. 2.4).

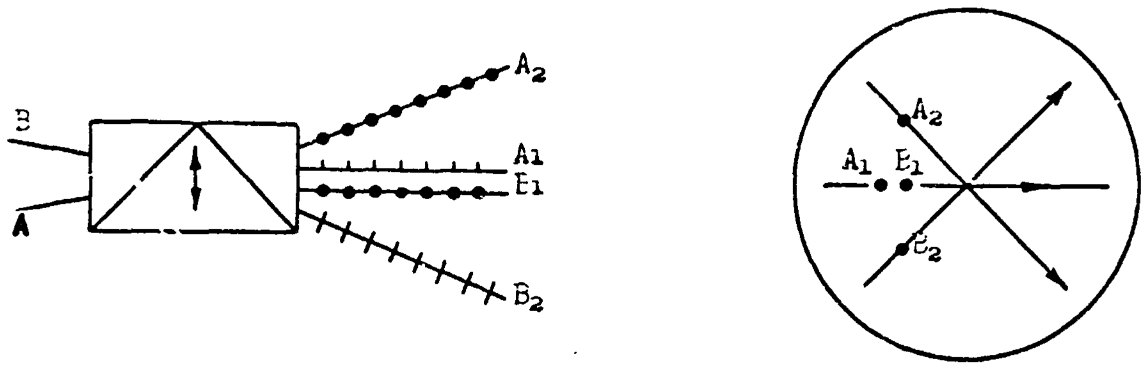


Figure 2.4: Image formation in a double symmetrical Wollaston prism. The diverging images A_2 and B_2 are screened off. From [Danjon, 1960] .

By displacing the Wollaston prism, hereafter called W-prism, parallel to the optical axis of the telescope, the images A_1 and B_1 can be kept parallel while they traverse the central part of the field of view. The usable part of the field is delineated by four wires of the reticule. To maintain parallelism of the images, the W-prism has to be displaced at a speed equal to that of the images A_1 and B_1. The diverging images A_2 and B_2 are screened off.

The W-prism is driven by a motor-micrometer that carries electrical contacts which trigger time pulses. The speed of the motor, driving the micrometer and W-prism, can be set proportional to the cosine of the latitude of the observing station. The micrometer settings corresponding to the triggered time pulses are recorded photographically. Since the operator has to make only slight adjustments in the traversing speed of the motor-micrometer by means of a handwheel, the results of the observations are virtually impersonal.

Figure 2.5: The Danjon impersonal prismatic astrolabe at the U.S. Naval Observatory. With the handwheel below the oculars the operator adjusts the speed of the motor-micrometer which drives the Wollaston prism. (Official U.S. Navy photograph.)

The OPL model has an aperature of 10 cm and a focal length of 100 cm. The optical path is folded to render the instrument more compact. A full view of the Danjon impersonal astrolabe is shown in Figure 2.5.

Astrolabe observations of stars as they transit across the instrumental almucantar establish a linear relationship between time, latitude, and the star's declination. The instrumental almucantar is defined as the circle of apparent altitude which is equal to the effective main prism angle.

In the OPL astrolabe the actual coincidence of the two images does not only depend on the zenith distance of the star and the effective angle of the main prism, but also on the position of the W-prism with respect to the focal plane of the instrument. The position of the W-prism at which the star crosses the almucantar is given when the primary optical plane of the W-prism coincides with the focal plane. Let us designate this position of the W-prism as zero position. The micrometer screw reading, corresponding to the zero position, shall be V.

The value of V varies during a night's observation slightly due to temperature changes within the instrument. It is usually determined before and after observations of a group of stars by means of a special autocollimator built into the instrument. From these readings, the value of V at the time of observation is usually determined by linear interpolation.

What has been said this far shows that each observed star has three sets of readings associated with it: the micrometer readings, the time pulses, and V. In addition, the azimuth of the star has to be recorded. The principle of reduction given below has been adapted from [Thomas, 1965, pp. B288-B292].

The photographic record of the observation of one star consists of the readings, x, of the position of the W-prism driving screw. The central position of the screw, which is very near to the zero position of the W-prism, is marked on the film by a light spot.

Let the micrometer readings be $x_1, x_2, \ldots x_n$, and the corresponding times, recorded with respect to a sidereal clock, be $t_1, t_2, \ldots t_n$. The mean micrometer reading will then be

$$x_0 = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{2.14}$$

which corresponds to the mean time of observation

$$t_0 = t + \frac{1}{n} \sum_{i=1}^{n} t_i , \tag{2.15}$$

where t is an arbitrary starting time. Let the zero position of the W-prism at t_0 be v_0, expressed in fractions of revolutions of the micrometer screw only. The whole number of revolutions, V_0, is given by the central position mark on the film record. This means that V can be assigned to the same arbitrary zero to which the x's refer. It follows that at t_0 we have for the zero position of the W-prism,

$$V = V_0 + v_0. \tag{2.16}$$

Let the effective angle of the main prism (the equilateral prism in front of the objective) at t_0 be $90° - z$. Then V corresponds to the apparent zenith distance of the alumcantar. The observed zenith distance, ζ', corresponding to x_0 will then be

$$\zeta' = z - s(x_0 - V), \tag{2.17}$$

where s is a scale factor.

Let

$$\eta' = \zeta' - z = s(V - x_0), \tag{2.18}$$

then η' represents the excess of the observed zenith distance over the zenith distance of the almucantar at time t_0. In Equation (2.18) second order terms which arise, owing to the fact that the rate of change of the zenith distance is not constant, can be neglected. The scale value s is usually an adopted value. It can be calculated for each star by

$$s = \frac{15 \left[\Delta T\right] \cos \Phi_0 \sin A}{\left[\Delta x\right]}, \tag{2.19}$$

where $\left[\Delta T\right]$ is the sum of the time intervals corresponding to the sum of the micrometer reading differences, $\left[\Delta x\right]$, Φ_0 and A are the adopted latitude of the station and the azimuth of the star, respectively. The observed zenith distance has to be corrected for refraction. Thus,

$$\zeta_0' = \zeta' + r, \tag{2.20}$$

where r is the refraction correction. Formulae for calculating r are given by [Bomford, 1962, pp. 265-267] and elsewhere.

A correction to η' is needed when a star is not observed symmetrically about the center of the field of view. The correction is [Thomas, 1965, pp. E290],

$$\eta = \eta' + c = \eta' + 1/4 \sin 2\zeta_0' \; (\Delta A)^2 \operatorname{cosec} 1'', \tag{2.21}$$

where ΔA in radians is the difference between the mean azimuth of the observed star and the azimuth of the center of the field of view. The latter needs to be determined from observations on stars at azimuths near 180°. Substituting Equations (2.20) and (2.21) into (2.18) we have

$$\eta = s(V - x_0) + r + c = \zeta_0 - z, \tag{2.22}$$

where $\zeta_0 = \zeta_0' + c$.

Now, let

$$z = z_0 + \;\; z, \tag{2.23}$$

where z_0 is exactly $30°$, corresponding to a nominal main prism angle of $60°$. The corrected observed zenith distance at time t_0 follows from (2.22) and (2.23) as

$$\zeta_0 = z_0 + \Delta z + \eta . \tag{2.24}$$

Let

$$AST = t_0 + \Delta t \quad , \tag{2.25}$$

where Δt is a correction to the clock. Further let the instantaneous latitude be

$$\Phi = \Phi_0 + \Delta\Phi \quad . \tag{2.26}$$

Assuming an error-free observation corrected for refraction and diurnal aberration, the observed zenith distance ζ_0 can be computed from formulae of spherical trigonometry. It is given by

$$\cos\zeta_0 = \sin\Phi \sin\delta + \cos\Phi \cos\delta \cos(\alpha - AST), \tag{2.27}$$

where α and δ are the apparent right ascension and declination of the star, assumed free of errors, referred to the true equinox and true equator of date.

For the zenith distance of the star corresponding to time t_0 and the adopted latitude, Φ_0, we can write three equations which can be derived from the astronomic triangle.

$$\cos\zeta_c = \sin\Phi_0 \sin\delta + \cos\Phi_0 \cos\delta \cos(\alpha - t_0) \tag{2.28}$$

$$\cos A \sin\zeta_c = \cos\Phi_0 \sin\delta - \sin\Phi_0 \cos\delta \cos(\alpha - t_0) \tag{2.29}$$

$$\sin A \sin\zeta_c = \cos\Phi_0 \sin(\alpha - t_0) \tag{2.30}$$

Substituting Equations (2.24), (2.25) and (2.26) into (2.27) and making use of (2.28) through (2.30), and taking $\cos\Delta z = \cos\Delta\Phi = 1$, and $\cos\Delta t = 1$, $\sin\Delta\Phi = \Delta\Phi$, $\sin\Delta t = \Delta t$, and $\sin\Delta z = \Delta z$, we get,

$$\cos A \sin\zeta_c + \Delta t \cos\Phi_0 \sin A \sin\zeta_c + \Delta z \sin(z_0 + \eta) = \cos(z_0 + \eta) - \cos\zeta_c . \tag{2.31}$$

Expressing Δt in seconds of time, $\Delta\Phi$, Δz, and $\Delta\psi = 15\Delta t \cos\Phi_0$ in seconds of arc, we get

$$\Delta\Phi \cos A \sin\zeta_c + \Delta\psi \sin A \sin\zeta_c + \Delta z \sin(z_0 + \eta) = \left[\cos(z_0 + \eta) - \cos\zeta_c\right] \operatorname{cosec} 1''. \tag{2.32}$$

Assumed is that Δt is small and that the star's coordinates are without errors.

Since $\zeta_c \cong z_0 \cong 30°$, we have

$$\left[\cos(z_0 + \eta) - \cos\zeta_c\right] \operatorname{cosec} 1'' = -1/2\,\eta, \tag{2.33}$$

hence the right-hand side of Equation (2.32) can be considered to contain the observed quantity η directly. Equation (2.32) obtained from several stars forms a system of equations that can be solved by a least squares method for the knowns $\Delta\Phi$, $\Delta\psi$ and ΔZ. From

$$\Delta t = \frac{\Delta\psi}{15 \cos\Phi_0} \tag{2.34}$$

Equation (2.25) can be solved for AST. In practice corrections are assigned to the observations for diurnal aberration, errors in star positions, and instrumental errors. Equations for the diurnal aberration correction are given in [Bomford, 1962, p. 260] and elsewhere.

2.221 Accuracy considerations

The accuracy of time determinations with the Danjon astrolabe is affected chiefly by observational errors and by errors in the adopted star positions. In order to reduce the errors due to errors in the star catalogue a so-called chain adjustment is made, which is based on the following principle.

First, a correction is calculated to reduce the right ascension of each star to a system defined by the right ascensions of all stars of a specific group only, i.e., the equinox of a specific group of stars.

Then, corrections are assigned to the equinox of the individual groups to reduce them to a common equinox, defined by the mean of the results from the first adjustment. A reference system is arrived at in this way which assures consistent solutions from observations on different stars. Although this chain adjustment is made, the stars that constitute the observing program are still based as a whole on a fundamental system such as the FK 4. Further details on this and other methods of adjusting star positions are given in [Danjon, 1960]. The method used at the RCO is discussed in detail in [Thomas, 1965].

In the latter publication observational results obtained with a slightly modified Danjon astrolabe are given for the years 1959 to 1963. From the published data the mean probable error in the determination of time was determined for August 1963 as ±4 milliseconds. The probable errors for one night's work range from ±3 to ±7 milliseconds.

2.23 The calculation of universal time from observed local sidereal time

We have seen that time observations with the PZT or astrolabe yield AST. The first step in the practical calculation of UT involves the conversion of AST to MST, which is nothing else than the equation of the equinox, Eq.E., given by

$$\text{Eq.E.} = \text{AST} - \text{MST}. \qquad (2.35)$$

The appropriate value of Eq.E. is found by interpolation in an ephemeris with the approximate UT of observation as argument. The approximate UT may be found for instance from the clock time of observation. MST is converted to GMST by adding the adopted longitude of the station to MST. In the practical operational procedure a table is constructed which gives GMST at 0^hUT for each calendar date. The equation used is

$$\text{GMST at } 0^h\text{UT} = 6^h38^m45^s.846 + 8640l^s.84542t + 0^s.0000093t^2, \qquad (2.36)$$

where t has the successive values 0.5, 1.5, 2.5, etc. divided by 365.25. At 12^hUT on January 0, 1900, t = 0. The epoch of UT, corresponding to the epoch of observation, is obtained by converting the elapsed mean sidereal interval, i.e., GMST - (GMST at 0^hUT), to a mean time interval with help of tables. An example of the conversion of AST to UT is given in [Nautical Almanac Offices, 1961, pp. 85].

Universal time, calculated in this manner, has an instantaneous value and is denoted UT0. To arrive at UT2, which is quasi-uniform, corrections are applied for the motion of the pole and seasonal variation in rotation speed of the Earth (see Chapter IV). Corrections due to variations in the direction of the local vertical are usually not applied but compensated by smoothing observations over a certain interval of time. Final universal time is given by

$$UT2 = UT0 + \Delta\lambda + \Delta S, \qquad (2.37)$$

where $\Delta\lambda$ is the polar motion correction and ΔS the seasonal variation correction.

It is clear that the observed value of UT2 depends on the knowledge of the precise angular difference between the meridian plane of the observer and the zero meridian plane, i.e., on the exact longitude of the observing station. Strictly speaking, each observatory determines its own zero meridian, hence its own system of UT2, owing to errors in its adopted longitude. The adopted longitude of a station is usually re-referred to as conventional longitude.

In order to bring different time determinations into closer agreement, international longitude campaigns were executed in 1926, 1933 and during and after the International Geophysical Year, 1957-1959.

Originally, the zero meridian plane to which all longitudes were referred was that passing through the transit telescope at the Royal Greenwich Observatory. In 1957 this observatory was moved to Herstmonceux. Since then the Bureau International de l'Heure determines a so-called mean observatory from observational data for UT2 of about 40 observatories, located about the world. The longitude of this mean observatory is defined to be zero. More will be said about the formation of the mean observatory in Section . .

The introduction of the mean observatory, however, does not invalidate the statement that each observatory determines its own system of UT2.

2.24 Accuracy of universal time determination

The USNO has compiled a comparison of universal time determined at Washington, Richmond, Herstmonceux (Greenwich), and Tokyo observatories during 1962 - 1963. The instruments used are PZT's, except for the period from July 1962 to September 1963, when a slightly modified Danjon astrolabe was used at Herstmonceux. The following table shows the results in the form $\Delta t_i = UT2_i - UT2_m$, where $UT2_i$ is the value of UT2 for each observatory, and $UT2_m$ is the mean value of UT2.

Table 2.2

Quarterly deviations, Δt_i, of UT2, in milliseconds
(Proceedings of the International Conference
on Chronometry, Lausanne, 1964)

Year	Quarter	Washington	Richmond	Greenwich	Tokyo
1962	I	+5	-4	-1	-1
	II	+5	-3	-2	0
	III	+4	-1	-9*	+5
	IV	+3	-6	+2*	+2
1963	I	-1	-7	+7*	+1
	II	-6	-7	+7*	+7
	III	-5	-6	+3*	+8
	IV	+1	-6	-2	+7
mean		0	-5	+1	+4
1962 - 1963		+7	+2	-6	-4

* astrolabe observations

The following table gives the standard error of observations for UT2 at 11 observatories for each tenth of a year compiled from observation data during 1956 to 1960 by the Mizusawa Observatory.

Table 2.3

Standard error of UT2 for 0.1 - year intervals, in milliseconds
(Proceedings of the International Conference on
Chronometry, Lausanne, 1964)

Station	Instruments	Standard error
Washington	PZT	± 3.6
Richmond	PZT	± 4.3
Greenwich	PZT	± 6.9
Ottawa	PZT	± 7.0
Mizusawa	PZT	± 8.9
Tokyo	PZT	± 4.5
Paris	Astrolabe	± 4.8
Potsdam	PI + Astrolabe	± 7.7
Buenos Aires	PI	± 5.7
Buenos Aires	PI	± 6.0
Moscow	PI	± 9.5

PI = passage instrument (meridian circle)

In conclusion it can be said with confidence that one year observations with the PZT or astrolabe yield a probable error in the determined universal time of about ± 2 milliseconds.

2.3 The Determination of the Ephemeris Time Epoch

Theoretically, ET is based on the motion of the Earth around the Sun, i.e., on Newcomb's theory of the Sun. In practice the correction, ΔT, to be applied to UT to give ET, may be obtained by comparing an observed position of a heavenly body in the solar system, recorded in

UT, with the gravitational ephemeris of that body, for which the argument is ET by definition.

The only requirement is that the gravitational theory of the observed body must be in accordance with the gravitational theory of the Sun. Since the Sun itself is not suitable for the rapid determination of ET, the IAU recommended in 1955 that ET should be determined from observations of the Moon whose theory of motion is sufficiently extensive [Markowitz, p. 93]. ET obtained from observations of celestial bodies is given by

$$ET = UT + \Delta T. \tag{2.38}$$

Formerly ΔT was obtained from observations of occultations of stars and from meridian observations of the Moon at certain phases. Nowadays the position of the Moon is usually obtained by photographing the Moon in the background of stars with the dual-rate Moon camera, whose principles of design and operation shall be briefly described.

2.31 The dual-rate Moon camera

The dual-rate Moon camera, designed by W. Markowitz, is a specialized photographic instrument that yields sharp photographic images of the Moon and surrounding stars simultaneously. An ordinary astronomic camera cannot be used successfully for photographing the Moon and stars on one plate, because of the much greater brightness and much faster motion of the Moon with respect to stars. With the dual-rate Moon camera these difficulties have been overcome and photographs may be made at any phase except near new Moon, and over a wide range in hour angle and altitude. It can be attached to visual or photographic refractors of about 200 mm aperature and about 200 cm to 600 cm focal length. A full

Figure 2.6: The Markowitz dual-rate Moon camera of the U.S. Naval Observatory. The motor, which drives the filter tilt arm is seen at the top of the camera. This camera was used in determining the fundamental frequency of caesium with respect to the ephemeris time interval. (Official U.S. Navy photograph.)

view of the Moon camera is shown in Figure 2.6. The principle of the camera is briefly the following [Markowitz, 1960a, pp. 107-114].

The photographic plate (blue sensitive) in the camera is driven at a sidereal rate by a motor the speed of which can be regulated according to the Moon's declination. During exposure the light rays from the Moon pass through a dark plane-parallel filter of 1.8 mm thickness and a diameter approximately equal to the apparent diameter of the Moon's image. The filter transmits about one five-hundredth of the incident light intensity and it is tilted such that it shifts the Moon's image by optical refraction. In effect the Moon is held fixed with respect to the stars by selecting the proper rate of tilt, which is a function of the relative speed of the Moon among the stars, and the orientation of the tilt axis. The tilt mechanism is driven by a second synchronomous motor and micrometer and can be shifted such that the axis of tilt is perpendicular to the apparent path of the Moon with respect to the stars. The epoch of the observation is the instant when the filter is parallel to the focal plane, since at that moment the Moon is not displaced. A contact is mounted on the tilt arm which triggers time pulses at the instant of parallelism that are recorded with respect to a mean time clock of high precision. The camera is rotated 180° between successive exposures and plates are always measured in pairs. Thus systematic errors due to imperfections in the filter or due to non-parallelism of filter and focal plane, are eliminated. Exposures are normally of 10 to 20 seconds duration, depending on the age of the moon. Under good conditions measurable images of stars with magnitude 9 are produced.

2.32 The determination of the equatorial coordinates of the Moon

The developed plate from the dual-rate Moon camera shows the image of the Moon in the surrounding star field. The method of calculating the geocentric equatorial coordinates, α_m and δ_m, of the Moon's center is in principle as follows [Markowitz, 1960a, pp. 107-114] and [Mueller, 1964, pp. 286-290]:

The images of the reference stars and the image of the Moon are measured with a measuring engine. The plates are prepared for measurement by marking the selected reference stars, and with help of a template, the approximate center of the Moon. The plate is positioned in the measuring engine with the marked center of the Moon near the center of a precision rotation stage. Using the x- and y- screws of the measuring engine the positions of the stars in x and y are measured to microns with respect to the center of the precision stage. These measurements are made twice, first in an initial position and then after rotating the stage through 180°.

The center of the Moon cannot be measured directly, due to the size of the image, but is determined from measurements of selected points along the bright limb. In the measurement one coordinate screw is held fixed at a position passing through the center of the stage, and the other is used to measure the radius of the Moon from the center to points on the limb at 6° intervals. Thus about 30 to 40 radii are obtained. The coordinates of the Moon's center are then determined by a least square approximation.

The observation equations are of the form

$$x_m \sin \Theta_i + y_m \cos \Theta_i + r = \rho_i, \tag{2.39}$$

where x_m, y_m, r are the unknown coordinates of the Moon's center and her radius, respectively, θ_i is the angle between the measured radius vector ρ_i and the coordinate axis held fixed, i.e., θ_i is a multiple of 6". Thus plate coordinates of the reference stars and the Moon's center are obtained in a common system.

The plate coordinates x_m, y_m and the topocentric equatorial coordinates α_m^* and δ_m^* of the moon are related through plate constants that have to be determined from the standard coordinates and plate coordinates of the reference stars.

In the absence of instrumental errors the photographic plate is parallel to an imaginary plane tangent to the celestial sphere. A plane rectangular coordinate system, $\bar{\xi}$, $\bar{\eta}$, is placed in the tangent plane such that the origin is at $\bar{o}$. The axis $\bar{\eta}$ is positive toward the celestial pole, i.e., in the direction of increasing declination, and the $\bar{\xi}$ axis is perpendicular to $\bar{\eta}$, positive in the direction of increasing right ascension. The projection of this system through the objective onto the plate is the standard coordinate system. The standard coordinates of a star are [Mueller, 1964, p. 311],

$$\xi = \frac{\cot\delta \sin(\alpha - \alpha_0)}{\cot\delta \cos(\alpha - \alpha_0) \cos\delta_0 + \sin\delta_0} \tag{2.40}$$

$$\eta = \frac{\cos\delta_0 - \cot\delta \cos(\alpha - \alpha_0) \sin\delta_0}{\cot\delta \cos(\alpha - \alpha_0) \cos\delta_0 + \sin\delta_0} ,$$

where α , δ are the star's right ascension and declination, respectively, α_0, δ_0 are the right ascension and declination of the origin of the plate coordinate system, i.e., of the center of the rotating stage. The coordinates α_0 and δ_0 may be obtained by interpolation between the reference stars.

The transformation between the x, y and ξ, η coordinates is needed because scale distortions in different directions are expected. The distortions may be due to centering and orientation errors of the coordinate system, non-perpendicularity of the x and y axes, astronomical refraction and aberration. If the zenith distance does not exceed 60° a linear transformation is sufficient, given by

$$\begin{aligned} \xi &= Ax + By + E \\ \eta &= Cx + Dy + F, \end{aligned} \tag{2.41}$$

where the coefficients A through F are the plate constants. These are a function of scale factors in the ξ and η directions, the angle between the ξ and x axes, and the standard coordinates of the true origin c'. A minimum of three stars are needed to solve for the six plate constants. In practice more than the minimum number of stars are measured (USNO practice is to measure 10 reference stars) and a solution for the plate constants is obtained by least squares. The standard coordinates, ξ_m and η_m, of the Moon's center are calculated from Equation (2.41), using the plate constants determined from the reference stars. Thus,

$$\begin{aligned} \xi_m &= Ax_m + Ey_m + E \\ \eta_m &= Cx_m + Dy_m + F. \end{aligned} \tag{2.42}$$

The topocentric equatorial coordinates of the Moon are from Equation (2.40) as follows:

$$\begin{aligned} \tan(\alpha^*_m - \alpha_o) &= \frac{\xi_m}{\cos\delta_o - \eta_m \sin\delta_o} \\ \tan\delta^*_m &= \frac{(\sin\delta_o + \eta_m \cos\delta_o)\cos(\alpha^*_m - \alpha_o)}{\cos\delta_o - \eta_m \sin\delta_o}. \end{aligned} \tag{2.43}$$

The topocentric coordinates of the Moon, calculated in the described manner, are corrected for geocentric parallax using adopted geocentric coordinates of the observing station. A method of calculating the geocentric parallax and an example are given in [Nautical Almanac Offices, 1961, pp. 60-62].

In addition to the parallax correction the coordinates of the Moon should be corrected for differential aberration due to the relative velocity of the moon with respect to the stars. Formulae for calculating the differential aberration are given in [Mueller, 1964, p. 316], and [Nautical Almanac Offices, 1961, pp. 51-52].

The results of the above described reduction method, or one similar, are apparent geocentric right ascension and declination of the Moon for a certain epoch of UT. The coordinates are referred to the true equator and equinox of the date by either updating the star coordinates from the epoch of the catalogue to the epoch of observation before determination of the plate constants, or by updating the derived coordinates of the Moon, if mean star coordinates are used as given in the catalogue. The star positions are taken from the Yale Zone catalogues and a correction to a fundamental catalogue (the FK 4 should be used) is applied.

2.33 The interpolation of ΔT

Since 1960 computed values of the apparent right ascension and declination of the moon, published in a national ephemeris, e.g., The American Ephemeris and Nautical Almanac, are calculated from Brown's lunar theory.

The coordinates are tabulated as a function of ephemeris time at hourly intervals to $0^{s}.001$ in right ascension and $0''.01$ in declination. These tables are entered with the observed coordinates of the Moon and

and two values of ET, corresponding to the UT of the observation are taken out by interpolation, with argument right ascension, and declination, respectively. The former is more reliable [Veis,1958, p. 124]. The two values are combined with suitable weights and the difference

$$\Delta T = ET - UT2$$

is obtained. An example is given in the Improved Lunar Ephemeris, 1952 - 1959, where the calculation of the lunar ephemeris is also described. Strictly speaking a distinction should be made between the theoretical value of ET and ET = UT2 + ΔT, when ΔT is obtained from observations of the Moon.

The practical determination of ΔT is affected by observational errors and by possible defects in the lunar (and solar) theories. The latter would obviously introduce systematic errors. Observational errors may be of systematic and random nature. Systematic effects arise from the unknown topography of the Moon. Due to libration the topography of the Moon's limb varies and introduces systematic errors in the measurement of the radii. The use of lunar profiles, e.g., Watts profiles, or charts in determining limb corrections reduces this effect.

A comparison of results from observations at the USNO during one lunation gave a probable error of $\pm 0\overset{''}{.}15$ in both coordinates of the Moon's center for each night [Markowitz, 1960a, p. 113]. From several lunations a probable error of $\pm 0\overset{''}{.}25$ was obtained. It is expected that adopting certain standard procedures in plate measurements, correcting for limb irregularities, and combining many observations will reduce the error in position to $\pm 0\overset{''}{.}02$ [Markowitz, 1954, p. 72].

III. FREQUENCY STANDARDS AND TIMEKEEPING

3.1 Introduction

Astronomical observations, as we have seen, furnish the epoch of time in one scale of time or another. The extrapolation of time from one epoch to the following, or stated differently, interpolation between successive epochs is performed by man-made clocks. Clocks provide intermediate epochs, and time interval.

The geodesist is chiefly concerned with the epoch of time, e.g., when observing celestial objects. The uniformity of the time interval is of greatest interest to the physicist, and to a lesser extent to the geodesist, e.g., when a satellite ephemeris needs to be established for which theoretically ephemeris time ought to be used.

The time interval between two events occuring at times t_1 and t_2, respectively, is $\Delta t = (t_2 - t_0) - (t_1 - t_0)$, where t_0 is the reference, i.e., the initial epoch. Thus, $\Delta t = t_2 - t_1$, which shows that the interval is independent of the initial epoch.

By its very nature, the time interval cannot be preserved for reference purposes; it has to be continuously reproduced by timekeeping devices. In order that the scale of time may be the same to every user, independent of his geographical location, it is necessary to calibrate local timekeeping devices against a recognized primary time standard. This primary standard is the Earth's rotation for rotational time, and at present so-called atomic clocks for uniform time, since ephemeris time is not readily available.

Obviously, the primary standards are inaccessible to most time users. Therefore, calibrations of local timekeepers against a primary standard is usually made through radio time or frequency broadcasts from national time services. It depends on the stability of the local time standards how frequently calibrations have to be performed.

In this chapter, man-made time and frequency standards will be discussed. Emphasis will be on modern timekeepers: quartz crystal and atomic clocks. Mechanical and electric clocks will be discussed briefly for the sake of completeness only.

In dealing with modern primary time standards as well as local precision timekeepers, which we shall call secondary time standards, a separation of time standards from frequency standards would result in undue duplication; there are no fundamental differences. They are based on dual aspects of the same phenomenon; frequency being the reciprocal of time interval. In fact, a standard of frequency can serve as a basis for time measurement, by referring the frequency to a desired time scale, e.g., atomic, sidereal, universal, and so forth. In other words, a modern precision clock is a frequency standard plus certain auxiliary equipment that, if in operation, displays a continuous record of time on a clock face or on other indicators. The time kept by the clock is only as accurate as the frequency of the oscillator that drives the clock.

In view of this close relationship, it seems justified to discuss frequency standards before discussing clocks. Similarly to the distinction made between primary and secondary time standards we will separate frequency standards into two groups. Primary frequency standards are those that have the highest accuracy, require no other reference, and are used where long term stability is of importance, e.g., for establishing a national time standard. Secondary frequency standards are those that have great short term stability and need to be compared to primary standards for reference.

3.2 Primary Frequency Standards

The search for an absolute frequency standard that is independent of the Earth's rotation and readily available led to investigations on the possibility of utilizing natural vibrations of atoms or molecules. This seems feasible since a variation of atomic constants is improbable. An atomic or molecular frequency standard provides constant frequency, immediately available uniform time intervals, and an accuracy superior to any previously known standard. Such a frequency standard is truly a primary standard requiring no other reference for calibration. The theoretical accuracy is of the order of one part in 10^{12} [Stecher, 1963, p. 169].

Since 1946 extensive research and development in the area of frequency standards has taken place. In principle, resonant frequency characteristics of atomic or molecular structures, low enough to permit evaluation with modern microwave techniques, are utilized. The choice of a particular element or compound depends largely upon practical considerations. One of the problems lies in the development of techniques to count the number of oscillations during a nominal time interval, which is of the order of 10^{10} oscillations per second.

To this writer's knowledge, workable primary standards at present are of only two types: atomic resonance standards and ammonia (NH_3) standards.

Atomic resonance standards use quantum mechanical effects, particularly transitions occuring between electron levels separated by energies corresponding to microwave frequencies. Transitions that are well suited occur in atoms of caesium, hydrogen, rubidium, and thallium. Devices utilizing these elements have been developed. Especially noteworthy are the caesium atomic beam and the hydrogen Maser (Maser = microwave amplifier by stimulated emission of radiation). Other standards in this group are the rubidium buffer gas cell, the rubidium Maser, and the thallium beam. With the exception of the rubidium buffer gas standard these devices are still in an experimental stage. The thallium beam devices are investigated in the USA and Switzerland. For details the reader is referred to [Bonanomi, 1962]. The rubidium buffer gas cell device is a secondary frequency standard and will be briefly discussed in Section 3.33.

Molecular standards, although they were the first developed, are to the writer's knowledge still in the experimental and testing stage. The most promising device is the ammonia Maser standard, developed by Townes, Zeiger and Gordon, in 1955. Ammonia Masers are in operation at several locations, e.g., at the NBS, the LSRH, in the USSR, and in Japan. Since the ammonia standards do not constitute a basis for a truly accepted primary frequency and time standard, they are not discussed further. For information the reader is referred to [Stecher, 1963] and [Shimoda, 1962].

Common to all atomic frequency standards are means for (1) selecting atoms at a suitable energy state, (2) enabling long life times in that state, (3) exposing these atoms to microwave energy, and (4) detecting the results [Hewlett-Packard, 1965, p. 2-1]. The caesium beam and hydrogen Maser standards have been developed as truly primary standards.

3.21 The caesium atomic beam standard

The caesium atomic beam was developed by L. Essen and J. V. L. Parry, in 1955 at the NPL. Since then, caesium beams have been installed at several places. In fact, the United States Frequency Standard is based since 1960 on the operation of two caesium beam units [Mockler et al., 1960]. The basic principle is briefly as follows [Hewlett-Packard, 1965, p. 2-1, 2-2], and [NBS, 1961, pp. 8-10]: Caesium (Cs) atoms have different energy levels and the atomic nuclei and electrons have magnetic moments. The moment or spin of the electrons may be parallel or antiparallel to the spin of the nucleus. The two cases differ by a certain amount of energy. By reversing the spin alignment, a transition occurs, i.e., the energy state of the atom changes. If the atom makes a transition from a higher to a lower energy level, a quantum of energy is emitted. In the reverse case a quantum of energy is absorbed. The frequency of this transition is detected by a suitable apparatus. For details on atomic transitions the reader is referred to [Trigg, 1964] or other text books on quantum mechanics.

In the caesium-133 atoms the transition frequency between so-called hyperfine ground states has been determined as 9, 192, 631, 770 cycles per ephemeris second. The interaction between the nuclei-electron magnetic moments, which produces this frequency, is usually denoted in the literature by $(F = 4, m_f = 0) \longleftrightarrow (F = 3, m_f = 0)$, where $F = 4$, $F = 3$ denotes certain energy levels of the Cs-133 atoms, and $m_f = 0$ stands for zero magnetic field.

The caesium atomic frequency standard is essentially a device for measuring wave length, called a spectrometer. Neutral Cs-atoms are emitted from an oven, A, (Figure 3.1) and are formed into a beam. The

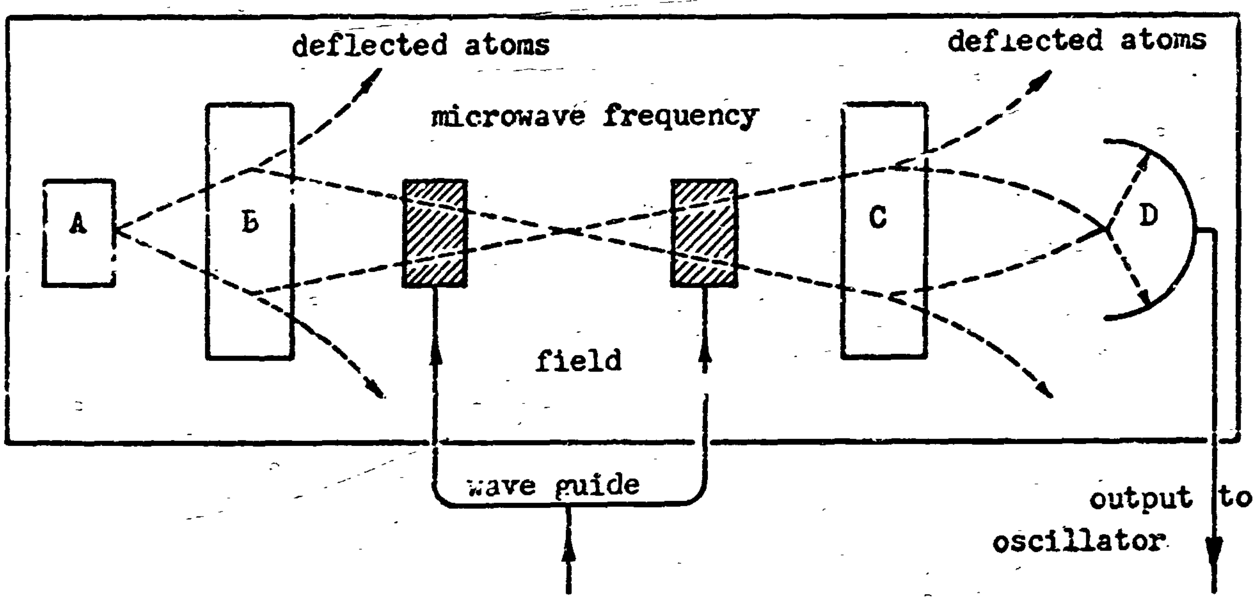


Figure 3.1: Schematic of a caesi tomic beam device.

beam passes through two non-homogenous magnetic fields. The first magnet, B, sorts out those atoms that have anti-parallel spin. Those with parallel spin, i.e., same direction of nuclei and electron spin, pass into a uniform magnetic field space and are excited by electromagnetic energy. At resonance (when the exciting microwave frequency equals the natural transition frequency of the atoms), change of state occurs by absorption or stimulated emission, depending on the initial state of the atoms. Upon passing through the second non-homogenous magnetic field, C, only those atoms that have undergone transition are focused on a hot wire detector, D.

If the frequency of the applied electromagnetic energy is not exactly equal to the transition frequency of the Cs-atoms, no transition occurs and no output signal is received from the detector. The frequency of the quartz crystal oscillator applying the electromagnetic field is regulated until a signal from the detector is received. When this is the case, the frequency of the oscillator equals the transition frequency of the caesium atom. Due to the fact that the caesium beam device works in conjunction with an external oscillator it is called a passive atomic resonator.

For details on caesium atomic frequency standards the reader is referred to the bibliography, especially to the articles by Bagley and Cutler, by Mockler, and to [NBS, 1961].

In recent years portable caesium standards have been developed. The stability of these small devices is of the order of 2 to 5 parts in 10^{11} [Markowitz, 1964a]. The caesium atomic standard manufactured by the National Company, Inc., Malden, Mass., is widely used and known as Atomichron. The following data is given by [Zacharias, 1957, pp. 63, 120]: advertised frequency stability of 1×10^{-11}; weight 500 lbs; height 7 feet; cost $50,000. The Hewlett-Packard Co., Palo Alto, Calif., produces a portable caesium beam standard with an advertised frequency stability of $\pm 2 \times 10^{-11}$. The price is $15,500 [Hewlett-Packard, 1965, p. AVI-1]. Other manufacturers of portable caesium standards are: Pickard and Burns, Inc., Needham, Mass.; Varian Associates, Palo Alto, Calif.; and Ebauches, S.A., Neuchâtel, Switzerland.

3.22 The hydrogen Maser

Probably the most noteworthy accomplishment in the field of atomic frequency standards during 1960-1962 has been the development of the hydrogen Maser by Goldenberg, Kleppner, and Ramsey at Harvard [Mockler, 1964, p. 523]. The basic principle is as follows [Hewlett-Packard, 1965, p. 2-1] and [Richardson, 1962, p. 59]:

The hydrogen Maser is an active atomic frequency standard; it provides constant frequency without being coupled to an external oscillator. The frequency is derived from stimulated emission of electromagnetic energy, i.e., from the energy release associated with transitions of atoms from a higher to a lower energy level. By means of special arrangements the interaction time between hydrogen atoms in high energy states (denoted $F = 1$, $m_f = 0$) and a microwave radio frequency field is lengthened to about one second. The long interaction time stimulates the desired radiation of energy. The radiated energy is amplified by electronic devices to a useful power level.

For details the reader is referred to the bibliography, especially to the articles by Ramsey, and by Vessot and Peters.

The frequency of a hydrogen Maser has been determined as 1, 420, 405, 751. 800 cycles per atomic second (A.1 system) at the Cruft Laboratories at Harvard in 1963 [Markowitz, 1964a]. A comparison between a Hewlett-Packard portable caesium standard and the hydrogen Maser operated at LBRH gave the frequency of the hydrogen Maser as 1, 420, 405, 751.778 ± 0.16 Hz. Hydrogen Masers have shown an extremely high frequency stability of ± 7 parts in 10^{13} over several months of operation [Vessot et al., 1964].

To this writer's knowledge hydrogen Masers have not yet come into widespread use. Extensive research and experiments are, however, going on and excellent results have been obtained. A portable hydrogen Maser has been developed by Varian Associates, Palo Alto, California.

3.3 Secondary Frequency Standards

Secondary frequency standards are those that must be referenced to a primary standard, either directly or by means of phase comparisons with radio signals. Quartz crystal oscillators have come into almost universal use as reliable secondary standards of high short term stability. The rubidium vapour standard, although an atomic standard, needs to be initially set with respect to a primary standard, such as the caesium beam. For this reason it is discussed in this section together with quartz crystal oscillators.

The basis of a quartz frequency standard (or quartz crystal clock) is a quartz crystal vibrator. In view of the following discussions of quartz frequency standards and quartz clocks a brief review of the principle of quartz oscillators and resonators seems appropriate.

3.31 Principle of quartz vibrators

The heart of every quartz based frequency and time standard is a quartz vibrator that controls the frequency of an electronic oscillator. Two properties make quartz an ideal vibrator: its piezo-electric property and its high mechanical and chemical stability. Due to the latter, it requires only a very small amount of energy to sustain oscillation; this fact is important since the amount of disturbance of the rate of oscillation, i.e., the frequency, is proportional to the amount of this energy. The piezo-electric property is as follows [Vigoureux, 1939, p. 1]:

If quartz crystals are subjected to compression in certain directions relative to two crystal faces, negative electric charges are produced at the edge between those faces, and positive electric charges at the opposite side of the crystal (the crystal becomes polarized). Conversely, if the crystal is placed between two electrodes of different electric potential, usually thin metallic coatings deposited on the crystal by evaporation, mechanical stresses are produced in certain directions within the crystal. The former phenomenon is called the direct piezo-electric effect, the latter the inverse piezo-electric effect.

If alternating electric current is applied to the electrodes, the crystal is set in mechanical vibration, the frequency of which is equal to that of the applied electric field. Resonance occurs when the applied frequency coincides with the natural frequency of vibration of the crystal. In this case, the amplitude of vibration becomes considerably large and correspondingly large direct piezo-electric effects are produced, which react on the electric circuit employed for establishing the difference of electric potential. The frequency at which resonance occurs is primarily dependent on the elastic properties of quartz and the dimensions and cut of the quartz element used. Usually quartz plates or rods are used in this manner in so-called quartz resonators, which can be employed as precision standards of frequency.

It is also possible to connect the quartz element to an electronic tube in such a way that self-maintained oscillations are generated [Vigoureux and Booth, 1950, pp. 89-106]. One of the best circuits for this purpose is the so-called Pierce circuit. In this circuit the impulses issuing from the piezo-electric effect are fed back to the quartz plate through the plate-grid capacitance of the tube. If the capacitance of the oscillatory circuit is less than the value which would make the frequency of the oscillatory circuit equal to the natural frequency of vibration of the quartz element, the impulse is fed back in the right phase. If the damping of the quartz is small, self-maintained oscillations are produced. Usually the piezo electric effects are amplified by electron tubes or transistors and a small amount of the amplified power is fed back to the crystal to sustain oscillation.

The resonant frequency of quartz crystals tends to drift higher with age. The drift is greatest after initial mounting and becomes almost constant after a certain period. This phenomenon, called aging, prevents the use of quartz vibrators as absolute standards of frequency. The frequency of vibration depends also on the temperature and pressure of the ambient air, and the crystal of an oscillator is therefore housed in a small oven.

Without going into fuller details it seems obvious from what has been said that the performance of a crystal oscillator depends to a large extent on the cut and mounting of the crystal, on the selection of the circuitry to sustain oscillation, on temperature and pressure control, and on the rate of aging. The theoretical limit of reliability of a quartz crystal controlled oscillator, provided all problems concerning mounting, etc., are solved, is given by the inherent stability of the quartz crystal itself.

Two specific types of quartz crystals are used nowadays in crystal oscillators of highest stability. These are the ring-crystal, developed by L. Essen in 1938 at the NPL, and the GT-plate, developed by W. P. Mason in 1940, at the Bell Telephone Laboratories. These crystals are frequently used in modified Pierce circuits or Maecham circuits. The latter uses a bridge to stabilize the amplitude of oscillation. Ultra-precise crystals of the GT-plate type and 2.5 Mz frequency are used in oscillators in connection with various caesium beam resonators. They are used, for instance, in precision quartz clocks at the USNO controlling transmissions.

For a detailed treatment of quartz resonators and oscillators, the reader is referred to [Vigoureux and Booth, 1950], which has been used extensively in this and the following section. The design and performance of ultra-precise 2.5 Mc/s crystal oscillators is described in [Warner, 1960, p. 1193].

3.32 Quartz standards

The most often used secondary frequency and time standards are quartz standards.

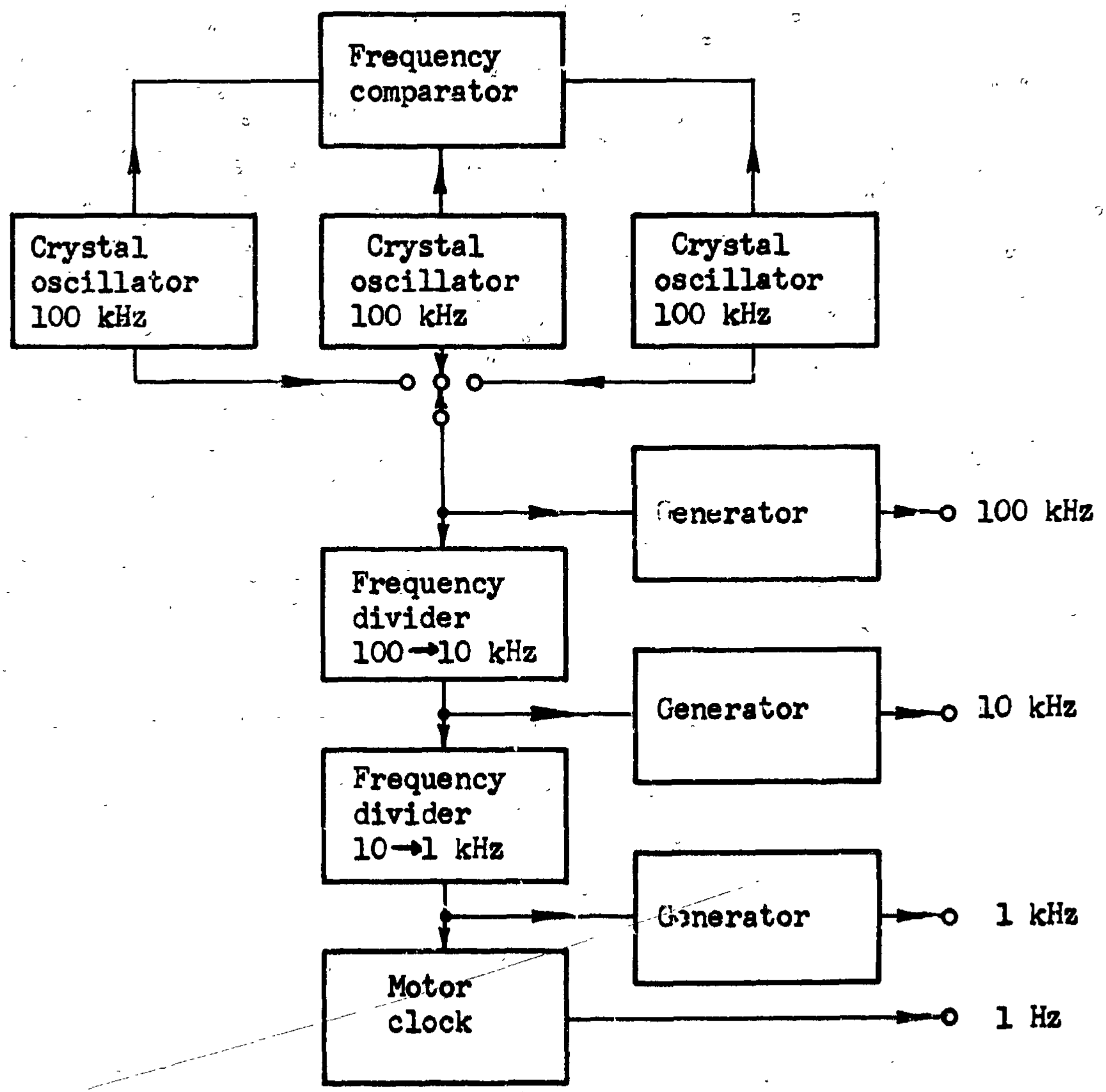


Figure 3.2: Schematic of a quartz crystal frequency standard.

In its basic form a quartz frequency standard consists of three independent crystal-controlled oscillators, nominal frequency say 100 kHz, with an electronic divider chain giving an output of one hundredth of the fundamental frequency, i.e., 1 kHz (Figure 3.2). This 1 kHz signal controls a motor geared to a clock mechanism, giving impulses at nominal one-second intervals.

The frequency of an oscillator is often expressed as a deviation from some nominal value. In the above example, for instance, assume that the clock mechanism keeps mean time. If the frequency is greater than 100 kHz the clock gains, if the frequency is less than 100 kHz the clock loses. Thus, if the daily clock gain is 0.0864 mean seconds, the mean frequency of the associated oscillator over the interval is usually given as + 1×10^{-6} from nominal. The deviation is a ratio. Calibration of frequency against time gives only the deviation of the mean frequency over the comparison interval. Variations about this mean are determined continuously and automatically by comparing the frequencies of the individual oscillators incorporated in the frequency standard.

From the early 1940's until about 1960, major services such as the NBS and the British Post Office, used quartz standards as the basis for precise time and frequency transmissions. The accuracy of the transmitted frequency for the NBS was about 1 part in 10^8.

Manufacturers of quartz oscillators used as frequency standards are too numerous to be listed here.

3.33 The rubidium vapor standard

The rubidium vapor standard is a recent development and offers high short term frequency stability in a small apparatus. The operation of the rubidium (Rb) standard is similar to the caesium beam in that it uses a passive atomic resonator to stabilize a quartz oscillator. It is based on atomic transitions occurring in Rb-87 atoms. It is a secondary standard because it must be calibrated against a primary standard, e.g., a caesium standard, during construction. The device uses a rubidium lamp to stimulate transitions of Rb-87 atoms. The frequency of the Rb vapor standard is 6, 834, 682, 614 Hz [Mockler, 1964, p. 524]. For details the reader is referred to the bibliography. especially to the articles by Arditi and Carver, and by Packard and Swartz.

The frequency of a rubidium vapor standard manufactured by Varian Associates was compared to A-1 for about seven months in 1963 and found to be constant to about 3 parts in 10^{11} [Markowitz, 1964a]. A long term stability of 1×10^{-11} or even 1×10^{-12} for rubidium vapor standards is predicted by [Arditi and Carver, 1964, p. 51]. A rubidium frequency standard weighing only 20 kg has been developed by General Technology Corporation, Torrance, California. The advertised long term stability after initial setting is 5×10^{-11} (standard deviation) for one year.

3.4 Clocks and Chronometers

The history of man-made timekeeping devices antidates the 20th century by about 3500 years. Throughout the ages improvements in timekeeping centered around the heart of every clock: an oscillatory device which depends upon resonance for the constancy of oscillation. Once a constantly oscillating device is found, i.e., a frequency standard, only some mechanisms such as dials or time indicators need to be added to constitute a complete clock.

In the following discussion the term clock is reserved for a device that is regulated with respect to a primary time standard, such as the Earth's rotation, or which constitutes a primary time standard itself, such as an atomic clock. Portable timekeepers of high precision are termed chronometers. They are of particular interest to the geodesist and for this reason a list of precision crystal chronometers is given in Section 3.421. Mechanical chronometers, although in common use, are not included.

For the sake of completeness we shall start with a very brief description of mechanical and electro-mechanical clocks. An interesting summary of the development of timekeepers from pre-history to the quartz clock may be found in [Harrison, 1948, p. 510-531].

3.41 Mechanical clocks

The first satisfactory oscillatory device was found to be the pendulum. C. Huygens, following an observation of G. Galileo, constructed the first pendulum clock in 1567. Since then, mechanical clocks employing a pendulum, or a balance wheel and hairspring in connection with an escapement to count the frequency of oscillations, have achieved a high state of precision. The source of power for these mechanical clocks are weights and springs, respectively. Time is usually indicated on a clock face through suitable mechanical gearing.

Electric clocks utilize electric currents as a source of power or as a means to sustain the oscillatory motion of a pendulum. The most famous of the electric clocks is a so-called free-pendulum clock, the Shortt clock. It consists of two separate clocks which operate in synchronization. The timekeeping element is a free swinging pendulum that receives an impulse from a falling lever every half minute. The lever is released by an electro-magnetic signal from the slave clock. Upon delivery of the impulse, a synchronizing signal is transmitted back to the slave clock in order to assure that the following impulse to the free pendulum is given exactly one half-minute after the preceding impulse. The pendulum swings in a temperature and pressure controlled chamber.

Shortt clocks were used at several observatories, e.g., at the USNO and at the RGO for determination and dissemination of precise time until the mid 1940's, when they were replaced by quartz crystal clocks, which in turn were superseded by atomic clocks. The accuracy of Shortt clocks is remarkably high, having a constant rate to about 2 milli-seconds per day. They are noteworthy for the fact that their use forced the introduction of mean sidereal time in the early 1930's. Before their development no clock had a sufficiently small rate to detect the difference between AST and MST. Other mechanical clocks with very high precision are the Riefler and the Leroy clocks.

3.42 Quartz crystal clocks

The fundamental difference between precision pendulum clocks, e.g., Shortt clock, and quartz crystal clocks, and atomic clocks for that matter, is that the latter do not incorporate an oscillatory device that depends on gravity for controlling the frequency of oscillations. Hence, a quartz clock or quartz chronometer will keep its rate at any geographical location, or if carried in an aircraft.

In effect the quartz crystal clock is a frequency standard. In principle it is similar to the equipment shown in Figure 3.2. Any oscillator capable of producing an accurate, precise frequency can be made the basis of a clock. However, since the frequency required for clock operation is 1 Hz and the frequency of the quartz vibrator is of the order of 0.1 MHz to 5 MHz, complex electronic frequency dividers are required to step down the frequency to a useful level for clock driving. Thus maintaining a time standard places additional requirements on top of those needed when maintaining a frequency standard alone. A complete quartz crystal clock in principle comprises one or more precision crystal oscillators, a frequency divider, and a clock, either synchronuous motor clock or decade counters.

Large quartz crystal clock assemblies have been used at major observatories since about 1942 in connection with astronomical time observations. Until the advent of the atomic frequency standards their drift rates were determined with respect to the Earth's rotation, corrected for known variations in rotation speed. Quartz crystal clocks have attained a high state of reliability. Using the best available crystals (CT-plate or ring-crystal) the day-to-day variation of a quartz clock based on a 2.5 MHz oscillator is about 0.2 microsecond [Markowitz, 1965]. The rate of the quartz clock associated with the caesium resonator at the USNO drifts about 0.01 microsecond per day due to aging of the crystal [Markowitz, 1962a, p. 11]. A concise account of the development of quartz crystal clocks is given in [Marrison, 1948, pp. 523-560].

5.421 Portable quartz crystal chronometers

Portable precision timekeepers are of greatest interest to the geodesist. Portable, compact quartz chronometer units or portable assemblies of oscillator, frequency divider and clock, have appeared on the market in large numbers since about 1960 and are met more and more frequently. In fact, they have become almost indispensable in connection

Table 3.1

Commercially available quartz crystal chronometers

Manufacturer and Product Discription	Advertised Accuracy, Temp. Range	Approximate Dimensions (cm)	Power Supply	Output	Remarks
Sperry Gyroscope Co., Brentford, Middlesex, England. (Crystal controlled chronometer.)	2×10^{-6} -20°to+50°C.	26x26x21	mains or battery, 12-14V d.c.	2 pps.	transistorized, ovened at 50°C. Price(1960): $500.
Venner Electronics, New Malden, Surrey, England. (Transistorized crystal clock type TSA 33)	3×10^{-6} +15°to+25°C.	30x20x18	mains or battery, 12V d.c.	10, 1 kHz 100, 50 Hz.	transistorized, not ovened. Price(1960): $400.
Communications Systems, Ltd., London, W.C.2, England. (The ATE Crystal Chronometer)	1×10^{-6} +10°to+30°C. 5×10^{-6} -10°to+55°C.	30x22x20	battery, 24 or 12V d.c.	square wave pulses at 1^s, 30^s, 1^m.	transistorized. Sidereal chronometer available. Price(1960): $400.
Ebauches, S. A., Neuchâtel, 6, Switzerland. (Quartz-clock type B-243)	1×10^{-7} 0°to+40°C. below 0°C. with modification.	46x38x33 W. 27kg	mains or battery, 12V d.c.	100,10,1 kHz, 200, 50 Hz. Seconds ticks accurate to 1 msec, 59th second omitted.	ovened at 58°C. Price(1960): $1,840. Battery unit: $522.
Omega, S. A., Bienne, Switzerland. (Omega Time Recorder)	$0^s.1$/day at all temperatures.	41x35x17 W. 18kg	battery, 6V d.c.	chronograph print-out to $0^s.01$, interpolation to 1 msec possible.	ovened at 60°C. Price(1960): $1,960.

Table 3.1 cont'd

Manufacturer	Advertised Accuracy, Temp. Range	Approximate Dimensions (cm)	Power Supply	Output	Remarks
Patek Philippe, Geneva, Switzerland. (Chronotome Model 8)	1×10^{-6} $+4°$to$+36°$C.	24x14x10 W. 3.5kg	mains or battery, 6 or 12V d.c.	mechanical contact gives impulse every second.	not ovened. Frequency shifts due to temp. changes are compensated by special circuit.
E. Norrman Labs., Williams Bay, Wisc., U.S.A. (Model 304 Frequency-Time Standard)	1to2x10^{-7}	48x30x27 W. 10kg	battery, 24V d.c.	115V, 25 watt.	transistorized, ovened. Price(1961): $850.
LIP, S. A., Besançon, France	$\pm 0^{s}.1$/day, $+15°$to$+25°$C.	23x23x12 W. 5kg	mains or battery, 127V a.c., or 12V d.c.	4,1 kHz, 200, 50 Hz.	transistorized, not ovened. Includes synchronized clock face.
Patek Philippe, Geneva, Switzerland. (Chronotone Model CP)	$\pm 5 \times 10^{-7}$ $+4°$to$+36°$C., or± 5x10^{-7} $-10°$to$+50°$C. upon request	24x14x10 W. 3.8kg	battery, lasts one year	10, 1 kHz, 100,10,1 Hz.	not ovened, mechanical temp. compensation. Time can be set to $0^{s}.01$. Price(1963): $375.
Voumard Machine Co. Neuchatel, Switzerland (Isatome)	1 or 2x10^{-8} Test gave 5×10^{-8} at$+12°$to$36°$C	22x14x9 W. 5kg	mains or battery, 190to240V a.c. Battery can operate for 24^{h}.	100,10,1 kHz, 100 Hz. 5 msec. pulse every second.	ovened.

Table 3.1 cont'd

Manufacturer	Advertised Accuracy, Temp. Range	Approximate Dimensions (cm)	Power Supply	Output	Remarks
Rohde and Schwarz, Munich, Germany. (Midget Crystal Clock, type CAQ)	$<5 \times 10^{-8}$ +15°to+30°C. $<15\times10^{-8}$ 0°to+40°C.	54x17x38 W. 20kg	mains or external battery, 11to16V. Reserve internal battery operates for 12^h.	sinusoidal 100, 10, 1 kHz, 50 Hz. Seconds tick $0^s.1$, minutes tick 1^s.	ovened. Either mean or sidereal clock unit. Price(1963): $1,740.
Citizen Watch Co., Tokyo, Japan. (QEC-2, QEC-3)	$0^s.5$/day at +20°C	20x12x17 W. 3kg	mains or battery, 85-110V a.c., 5V d.c.	clock face.	temp. coefficient $0^s.1$/day at 0° to +40°C. Price(1963): $175.
Suwa Seikosha Co., Nagano-ken, Japan. (Crystal Chronometer)	2×10^{-6} 0°to+40°C.	16x20x6 W. 3.5kg	battery, 2.2to3.2V d.c.	mechanical contact produces tick every 30 seconds.	transistorized, not ovened. Temperature compensation device. Seconds hand adjustable at units of $0^s.2$. Price(1963): $300.
Tokyo Communication Equipment Co., Kanagawa-ken, Japan.	$0^s.2$/day at +20°C.	16x15x10 W. 1.5kg	mains or battery, 12V d.c.	$0^s.2$ pulse at 1^s, 1^m, and 1^h.	transistorized. Price(1963): $162.
Electročas National Corp., Prague,9,C.S.R. (Transistor quartz clock with radio synchronization)	5×10^{-8} without synchronization to radio signals.	58x50x42	mains or battery, 220V or 12V d.c.	100, 1 kHz, $0^s.1$ tick every sec., prolonged to $0^s.5$ at minute.	clock is synchronized to radio signal

Table 3.1 cont'd

Manufacturer	Advertised Accuracy, Temp. Range	Approximate Dimensions (cm)	Power Supply	Output	Remarks
Tractor Inc. Austin, Tex., U.S.A. (Portable clock, Model A5-5, Model A5-2.5)	Model A5-5 10 μsec/day Model A5-2.5 2 μsec/day	15x51x31 w. 19kg	mains 100-130V a.c., or 200-260V a.c. Internal battery for 15^h operation.	Sine wave at 5, 1 MHz, 100, 10 kHz. Pulse output to 1 pps.	24^h register showing hours, min. & sec. Adjustment to radio signal to μsec. Automatic change from mains to battery. Indicator to register shock in excess of 5 G.
Newtek, Inc. Woodside, N.Y., USA (Chronofax Model 103)	0.5 msec/day -40°to60°C.	30x33x13 w. 8kg	internal 28V battery for 24^h operation. Mains, with power pack.	time printed out in hours, min. sec. Last count 1 msec.	prints time of any event to 1 msec. See section 6.232. Price (1965): $10,000. Time correlator $2,000. Power pack available.

Notation to Table 3.1: a.c. = alternating current
d.c. = direct current
V = Volt
Hz = cycles per second
temp. = temperature
chron. = chronometer
C. = Celsius
w. = weight

All entries are compact portable chronometers to this writer's knowledge.

with observations of artificial satellites, where timing accuracy is of utmost importance. To most units automatic printing equipment may be attached (if not part of it) that prints out the exact epoch of any incoming signal, e.g., from star observations or radio signals, to fractions of seconds.

Some of the commercially available crystal chronometers are listed in Table 3.1. The table is based on information contained in circulars 1, 1A, 1B, and 1C, "Commercially Available Portable Crystal Chronometers", distributed between 1960 and 1963 to members of Special Study Group No. 4 of the International Association of Geodesy, by A. R. Robbins, head of the study group. Additions were made according to information provided directly by manufacturers. In all cases the listed data is based on manufacturer's description. Quoted prices are only meant to indicate price range and may have changed since the data was compiled.

3.43 Atomic clocks

Actually there exists no device that fits the label "atomic clock." The term has been assigned to quartz oscillators which are stabilized in frequency by an atomic resonator. The clock itself is driven by the oscillator's frequency output. In the literature often, and appropriately, no distinction is made between atomic frequency standards and atomic clocks. In the case of the caesium atomic resonator, for instance, it is feasible to associate a precision quartz crystal clock with the caesium resonator, and the whole setup is then termed a caesium atomic clock which keeps a particular atomic time. A typical example of a caesium atomic clock is the Master clock of the USNO.

"The Master clock, which is a combination of atomic resonator, quartz crystal oscillator, and clock movement, constitutes an atomic clock in the sense that time is shown in hours, minutes, seconds, and fractions, and the rate is governed by oscillations produced by the caesium atom" [Markowitz, 1962a, p. 11].

Atomic frequency standards have been described already in Section 3.2 and not much more can be added here. However, in order that the concept of an atomic clock or atomic time standard may be fully understood, the Master clock of the USNO, will be described, based on [Markowitz, 1962a, pp. 10-11]. The Master clock which determines standard time for the United States is shown in Figure 3.3.

The caesium beam atomic resonator, an Atomichron (see Section 3.21), controls the frequency of the clock system. The frequency is stable over several months to about ± 1 part in 10^{10}. Day-to-day variations within a month, do not exceed ±1 part in 10^{11}. The atomic resonator is operated about 2 hours each day and it is used to check the frequency of a 2.5 MHz quartz crystal oscillator manufactured by the Western Electric Company. The 2.5 MHz frequency is divided electronically to produce an output of 100 kHz, which is fed to a clock made by the Hewlett-Packard Company. The clock consists of another electronic divider, clock movement, and seconds pulser. The 100 kHz frequency is further divided to 1 kHz which drives a synchronous motor. The motor is geared to indicate hours, minutes and seconds. The pulses are produced once per second and are spaced evenly with a precision of about 0.01 microsecond.

It is the seconds pulses that are used as precise reference for the astronomical observations, e.g., PZT and Moon camera observations. Although the caesium resonator is not operated continuously for it is a complex device, the oscillator and clock are operated without stopping for years. They are driven by storage batteries which are continuously recharged.

The oscillator frequency is offset by a fixed amount to compensate for the aging of the crystal (about 1 x 10^{-7} sec/day). It is also offset from the atomic frequency so that the time interval kept by the clock is close to the mean time interval (UT2 system). The offset is explained in Section 5.2.

3.431 Portable atomic clocks

Portable atomic clocks may be formed by associating suitable high precision oscillators, frequency dividers and clocks (either synchronomous motor clocks or decade counters) with portable atomic frequency standards. Manufacturers of such portable frequency standards have been mentioned in Sections 3.21 and 3.22, respectively.

Figure 3.3: The Master clock room of the USNO. The caesium resonator, an Atomichron, is in the cabinet to the right. (Official U.S. Navy photograph.)

IV. VARIATIONS IN ROTATIONAL TIME AND RELATED TOPICS

4.1 Introduction

It has been mentioned repeatedly that the rate of the Earth's rotation is variable. Consequently, any time system which is based on the Earth's rotation is rendered non-uniform. The effect of the variations in the rotation speed of the Earth on rotational time is the same for all geographic locations.

Another phenomenon, polar motion, causes variations in the position of the meridian, hence, a variation in longitude, and consequently, in time. The effect of polar motion on rotational time is different for each geographic location.

In this chapter a brief outline of the effects of the variation in rotation speed and polar motion will be presented. No effort is made to provide an insight into the major theories concerning the causes of these phenomena. Instead, accepting the variations in rotational speed and polar motion as facts some principal observational methods of detecting the magnitude of the variations, and adopted ways to compensate for them, will be outlined.

The practical aim of all techniques of determining and correcting for the variations in the rotational speed of the Earth and the motion of the pole is a time system, as uniform as practical, and yet in accordance with the rotation of the Earth. Such a time system is the UT2 system.

4.2 Polar Motion

The Earth rotates about an instantaneous axis. Owing to the gravitational attraction of the Sun, Moon, and planets on the equatorial bulge of the Earth, the orientation of the instantaneous axis in space changes.

The secular part of this motion is termed precession, the periodic part is collectively called nutation.

The term polar motion refers to the motion of the terrestial pole of the Earth with respect to a fixed point on the surface of the Earth. Polar motion has periodic terms of 12-month and 14-month, and a still widely debated secular term. Unlike precession and nutation, these terms are not due to gravitation.

In the literature the term variation of latitude is often used in lieu of polar motion. Although the magnitude of the variation in the pole's position is generally determined from latitude observations, the expression is a poor choice since longitude and azimuth both vary due to the motion of the pole as well.

Polar motion was discovered by F. Küster in 1890. S. Chandler found in 1891-1892 the 12-month and 14-month periodic motions of the instantaneous pole about its mean position (Chandler-period). Following these discoveries an international institution, the International Latitude Service (ILS) was established in 1899 for the purpose of determining the total motion of the pole, i.e., to determine periodic and possibly secular variations in the pole's position. The ILS was reorganized in 1962 into the International Polar Motion Service (IPMS) following resolutions of the XIIth general assembly of the IAU at Berkeley in 1961. The central bureau of the IPMS is located at the Mizusawa Observatory, Japan, and its activities are directed by an international scientific council [Yumi, 1964]. In principle, the IPMS continues the work of the ILS.

Another institution, the Rapid Latitude Service (RLS) was established by action of the general assembly of the IAU at Dublin in 1955, and put under the direction of the BIH. The function of the RLS is to provide the coordinates of the instantaneous pole on a nearly current basis so that corrections to observed UT0 time may be derived with a minimum of delay. At present, corrections to observed time for the polar motion are strictly based on RLS results [Nautical Almanac Offices, 1961, p. 445].

The motion of the pole is usually determined from continuous latitude observations at so-called latitude observatories. At present there are about 33 such stations located about the world, some of them determine time and latitude simultaneously. Five of these stations are designated ILS stations, located at nearly the same latitude (39°08 N); only these are engaged in the determination of the total motion of the pole (see Table 4.1). The other stations primarily participate in the RLS program, which will be described in Section 4.24.

4.21 Principles of observation and reduction methods

Three types of instruments are used at the latitude observatories to determine the motion of the pole: the PZT, described in Section 2.21; the Danjon astrolabe, described in Section 2.22; and the zenith telescope.

The five ILS stations use zenith telescopes. The telescope, with focal length of about 130 cm, is mounted at the end of a counterbalanced horizontal axis. The tube is restrained to move in the plane of the meridian, and the telescope may be rotated about a vertical axis. A divided circle is used to set the instrument, but the observed latitude depends on the level and micrometer reading only. The probably error of the latitude for one nights observation is about $\pm 0\overset{''}{.}10$ [Markowitz, 1960, p. 223]. For details on zenith telescope observations the reader is referred to [Bomford, 1962, pp. 268-275].

The principle of latitude determination with the PZT and astrolabe has been given in Sections 2.21 and 2.22, respectively.

The method of observation of latitude used with the zenith telescopes at the five ILS stations is generally known as the Horrebow-Talcott method, whose principle is briefly as follows:

A star pair, consisting of one star to the north, the other to the south of the zenith, are observed at nearly the same altitude and time in the meridian. The telescope is reversed about its vertical axis between observations on the north and south star. The inclination of the optical axis is maintained in the two positions by means of spirit (Horrebow) levels. Micrometer readings are taken on each star which, through application of a scale factor, are a measure of the zenith distance difference. The latitude is given by

$$\Phi = 1/2 \left[\delta_s + \delta_n + (r_s - r_n)\right], \tag{4.1}$$

where δ_n and δ_s are the known declinations of the north and south star, respectively; and r_n and r_s are the micrometer readings on the north and south star, converted into arc. The Horrebow-Talcott method is fully described in [Hoskinson and Duerksen, 1947, pp. 63-82], and in [Bomford, 1962, pp. 268-281].

The PZT method described in Section 2.21, is in fact similar to the Horrebow-Talcott method. With the PZT, $\delta_n = \delta_s$, because of the rotation of the plate through 180° when observing the same star near the zenith. The quantity $(r_s - r_n)$ is determined from the photographic plate with a measuring engine.

In all three methods observations are made at equal or nearly equal altitudes, on opposite sides of the zenith, in order to reduce the effect of refraction anomalies.

The latitude determined is directly affected by possible errors in the declinations of the stars used, and also by any systematic errors in the proper motions of the stars.

One method to avoid these errors is to place three or more stations on the same parallel of latitude. If these stations observe the same stars all the time, changes in the latitudes of these stations can be determined which are free of the above mentioned errors.

The ILS stations, located at about the same latitude of +39°08 observe the same groups of stars, which are changed periodically. Due to weather conditions they cannot always observe the same stars. Asymmetries are compensated by an internal adjustment of the observations and have a small second order effect on the derived position of the pole [Markowitz, 1960c, p. 327].

4.22 The effect of polar motion on latitude and longitude

It is customary to describe the position of the instantaneous pole in a plane rectangular coordinate system with origin at some defined mean pole. The coordinate system is chosen such that the positive X-axis is along the mean Greenwich meridian and the positive Y-axis is directed along the meridian 90° to the west, as shown in Figure 4.1a.

Equations expressing the effect of the motion of the pole on the latitude and longitude of an arbitrary station may be derived from Figure 4.1b.

A transformation between the mean $\bar{X},\bar{Y},\bar{Z}$, and instantaneous X', Y', Z', rectangular coordinates of an arbitrary station will be of the form

$$\begin{bmatrix}\bar{X}\\ \bar{Y}\\ \bar{Z}\end{bmatrix} = R\begin{bmatrix}X'\\ Y'\\ Z'\end{bmatrix}, \qquad (4.2)$$

where the elements of the matrix R are functions of the coordinates, x, y (in seconds of arc) of the instantaneous pole.

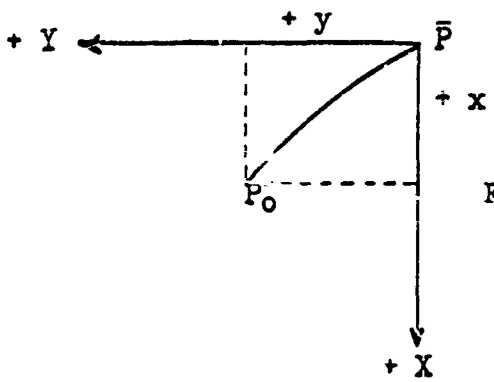


Figure 4.1 a:

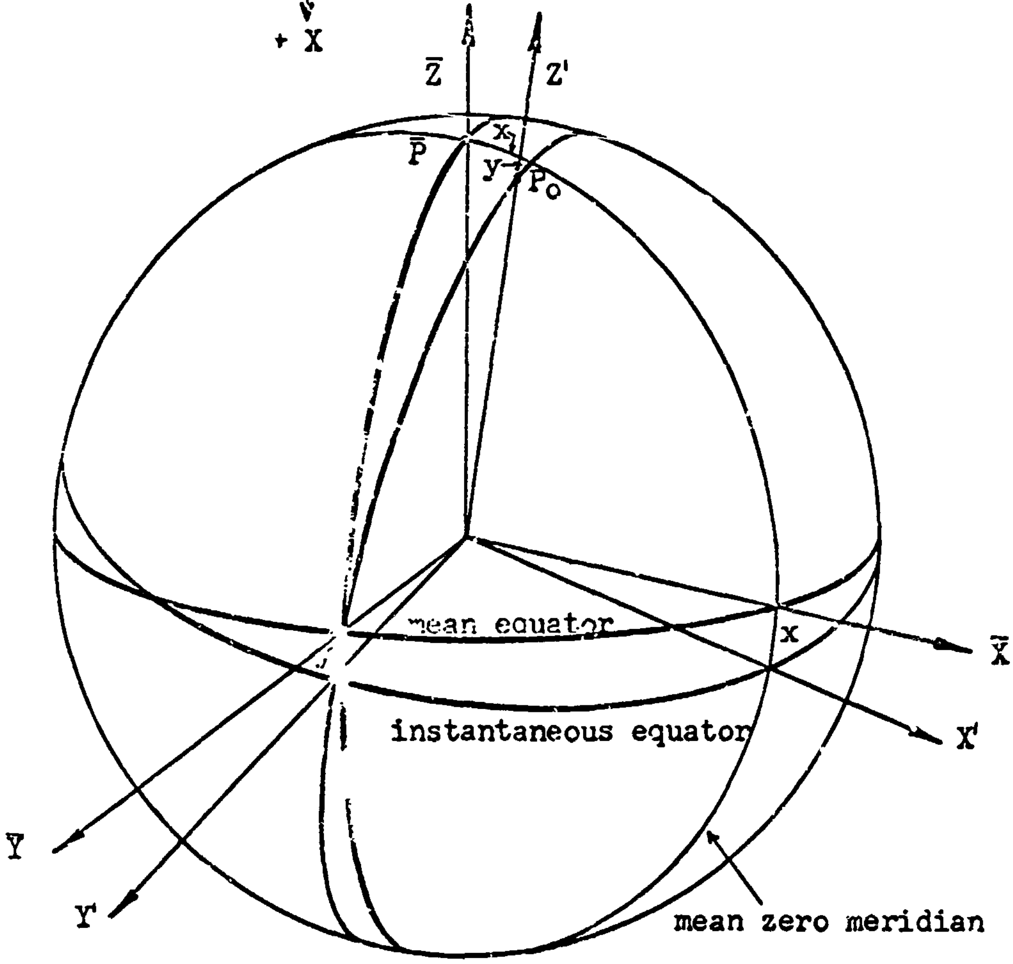


Figure 4.1 b: The effect of the motion of the pole on latitude and longitude. $\bar{P}$ and P_o are the mean and instantaneous pole, respectively.

$$R = \begin{bmatrix} \cos(X'\bar{X}) & \cos(Y'\bar{X}) & \cos(Z'\bar{X}) \\ \cos(X'\bar{Y}) & \cos(Y'\bar{Y}) & \cos(Z'\bar{Y}) \\ \cos(X'\bar{Z}) & \cos(Y'\bar{Z}) & \cos(Z'\bar{Z}) \end{bmatrix},$$

where the direction cosines are as follows:

$$\begin{aligned} &\cos(X'\bar{X}) = \cos x; && \cos(Y'\bar{X}) = \sin x \sin y; && \cos(Z'\bar{X}) = \sin x \cos y \\ &\cos(X'\bar{Y}) = 0 && \cos(Y'\bar{Y}) = \cos y && \cos(Z'\bar{Y}) = \sin y \\ &\cos(X'\bar{Z}) = -\sin x; && \cos(Y'\bar{Z}) = -\sin y \cos x; && \cos(Z'\bar{Z}) = \cos x \cos y. \end{aligned}$$

Since x and y are small quantities, we may set $\cos x = \cos y = 1$, $\sin x = x$, and $\sin y = y$. After appropriate substitution we get, neglecting products xy,

$$R = \begin{bmatrix} 1 & 0 & +x \\ 0 & 1 & +y \\ -x & -y & 1 \end{bmatrix}. \tag{4.3}$$

The relationship between the geodetic coordinates Φ, Λ, and the components of unit vectors X, Y, Z, of any point are (assuming the Earth to be a sphere of unit radius)

$$\begin{aligned} X &= \cos\Phi\cos\Lambda \\ Y &= -\cos\Phi\sin\Lambda \\ Z &= \sin\Phi . \end{aligned} \tag{4.4}$$

Substitution of (4.4) and (4.3) into (4.2) yields

$$\begin{bmatrix} \cos\Phi_m \cos\Lambda_m \\ -\cos\Phi_m \sin\Lambda_m \\ \sin\Phi_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & +x \\ 0 & 1 & +y \\ -x & -y & 1 \end{bmatrix} \begin{bmatrix} \cos\Phi_0 \cos\Lambda_0 \\ -\cos\Phi_0 \sin\Lambda_0 \\ \sin\Phi_0 \end{bmatrix},$$

where Φ_m, Λ_m, and Φ_0, Λ_0 refer to the mean (fixed) and instantaneous (observed) latitude and longitude, respectively.

Multiplying we get

$$\cos\Phi_m \cos\Lambda_m = \cos\Phi_0 \cos\Lambda_0 + x \sin\Phi_0, \tag{4.5}$$
$$-\cos\Phi_m \sin\Lambda_m = -\cos\Phi_0 \sin\Lambda_0 + y \sin\Phi_0, \tag{4.6}$$
$$\sin\Phi_m = -x\cos\Phi_0 \cos\Lambda_0 + y\cos\Phi_0 \sin\Lambda_0 + \sin\Phi_0 . \tag{4.7}$$

From (4.7) it follows that

$$\sin\Phi_m = \sin\Phi_0 + \cos\Phi_0 (y \sin\Lambda_0 - x \cos\Lambda_0) . \tag{4.8}$$

According to Taylor's expansion we can write (since Φ_0 and Φ_m are nearly equal),

$$\sin \Phi_m = \sin \Phi_0 + (\Phi_m - \Phi_0) \cos \Phi_0 + \cdots,$$

from which follows

$$\sin \Phi_0 + (\Phi_m - \Phi_0) \cos \Phi_0 = + \sin \Phi_0 + \cos \Phi_0 \, (y \sin \Lambda_0 - x \cos \Lambda_0),$$

and consequently ,

$$\Delta\Phi = \Phi_m - \Phi_0 = y \sin \Lambda_0 - x \cos \Lambda_0 \, . \qquad (4.9)$$

From an extended observation program of many stations i observation equations are set up which are of the form

$$\Phi_0^i - \Phi_m^i = x \cos \Lambda_0^i - y \sin \Lambda_0^i + z, \qquad (4.10)$$

where Φ_0^i is the observed latitude, Φ_m^i is an adopted latitude for an initial epoch, Λ_0^i is the instantaneous longitude of the station, and z is an unknown that is included to allow for errors that affect all stations using the same observing program alike, such as errors in proper motions and star coordinates. Equation (4.10) is solved by a least squares approximation for x,y,and z. x and y are the coordinates of the instantaneous pole, which are referred to the mean pole of a certain epoch (the same epoch to which the adopted coordinates of the stations refer to) [Markowitz, 1961, p.31].

The equation for the effect of polar motion on the longitude of a station follows from Equation (4.5), which reads

$$\cos \Phi_m \cos \Lambda_m = \cos \Phi_0 \cos \Lambda_0 + x \sin \Phi_0 .$$

From (4.9) we have

$$\Phi_0 = \Phi_m - (y \sin \Lambda_0 - x \cos \Lambda_0) = \Phi_m - \Delta\Phi .$$

$\Delta\Phi$ is, however, small and we can let $\sin \Delta\Phi = \Delta\Phi$, and $\cos \Delta\Phi = 1$.

Then,

$$\sin \Phi_0 = \sin \Phi_m - \cos \Phi_m \Delta\Phi, \qquad (4.11)$$

$$\cos \Phi_0 = \cos \Phi_m + \sin \Phi_m \Delta\Phi. \qquad (4.12)$$

Let $\Lambda_o = (\Lambda_m - \Delta\lambda)$, then, treating the small quantity $\Delta\lambda$ similarly as $\Delta\Phi$, we get

$$\cos\Lambda_o = \cos\ (\Lambda_m - \Delta\lambda) = \cos\Lambda_m + \sin\Lambda_m \Delta\lambda\ . \qquad (4.13)$$

Substituting (4.11), (4.12), and (4.13) into (4.5), multiplying and dropping second order terms, e.g., xy, x^2, $x\Delta\lambda$, etc., and further assuming that $\sin\Lambda_m \cong \sin\Lambda_o$, and $\cos\Lambda_m \cong \cos\Lambda_o$, we get (neglecting the index for Λ),

$$\cos\Phi_m \cos\Lambda = x \sin\Phi_m + \cos\Phi_m \cos\Lambda + \cos\Phi_m \sin\Lambda \quad +$$
$$y \sin\Phi_m \cos\Lambda \quad \sin\Lambda - x \sin\Phi_m \cos^2\Lambda\ ,$$

from which, after replacing $\cos^2\Lambda$ by $1 - \sin^2\Lambda$, dividing through by $\cos\Phi_m \sin\Lambda$, and rearranging, we finally get

$$-\Delta\lambda = (y \cos\Lambda + x \sin\Lambda\ ) \tan\Phi_m. \qquad (4.14)$$

Since $\Delta\lambda = \Lambda_m - \Lambda_o$, we have for an arbitrary station i

$$\Lambda_m^i - \Lambda_o^i = -(y \cos\Lambda^i + x \sin\Lambda^i) \tan\Phi_m^i. \qquad (4.15)$$

Observation equations of the form

$$\Lambda_o^i - \Lambda_m^i = (y \cos\Lambda^i + x \sin\Lambda^i) \tan\Phi_m^i + d \qquad (4.16)$$

could be used in the same manner as Equation (4.10) to solve for the coordinates of the pole by a least squares approximation. The quantity d has the same meaning as z in Equation (4.10).

For completeness sake, the azimuth equation shall be stated without derivation as given by [Bomford, 1962, p. 329]:

$$A_m - A_o = -(x \sin\Lambda + y \cos\Lambda\ ) \sec\Phi_m. \qquad (4.17)$$

Equations (4.9), (4.15), and (4.17) may be derived using standard formulae of spherical trigonometry. A solution is given by [Baeschlin, 1948, pp. 867-871].

In practice, Equation (4.10) is solved for x, y, and z. Using these results, corrections to longitude, hence time, are calculated from

Equation (4.15). It has been proposed by [Markowitz, 1961, pp. 36-37] and [Murray, 1961, pp. 69-77] to utilize results from PZT and astrolabe observations (both instruments determine time and latitude simultaneously). The solution for the x, y coordinates of the pole would then come from a combination of Equations (4.10) and (4.16).

Observations from two stations located on the same parallel, and using the same star program, would yield two equations for the differences in observed latitude and time, as follows:

$$d\bar{\Phi} = ax + by + z \tag{4.18}$$

$$d\lambda = 1/15\ (bx - ay)\ \tan\bar{\Phi} + d, \tag{4.19}$$

where $a = \cos\Lambda_1 - \cos\Lambda_2$, and $b = \sin\Lambda_2 - \sin\Lambda_1$; $d\bar{\Phi} = \Delta\bar{\Phi}_2 - \Delta\bar{\Phi}_1$ and $d\lambda = \Delta\lambda_2 - \Delta\lambda_1$.

Two stations will give a solution for x and y, a third station on the same parallel would allow a solution for z and d also. Further details are given in the articles by Markowitz and Murray, mentioned above.

It should be mentioned that astronomic latitude, longitude, and azimuth, determined by any of the methods commonly used in geodetic astronomy need to be corrected for the motion of the pole. The corrections are calculated by means of Equations (4.9), (4.15), and (4.17) in exactly the form given here (see also Section 6.51). In the practical evaluation of the sine and cosine in these expressions, either Λ_m or Λ_0 may be used.

4.23 The total motion of the pole and the IPMS

It was mentioned before that the IPMS is primarily concerned with the total motion of the pole. In principle, Equation (4.10) is solved by least squares for the coordinates of the pole. The observational data is obtained from the five ILS stations located as given in Table 4.1 below [Yumi, 1965, p. 3].

Table 4.1

International latitude observatories of the IPMS

Station	Longitude	Latitude (1900-1905)
Carloforte, Italy	+ 8° 18' 44"	+39° 08' 08".941
Gaithersburg, USA	- 77 11 57	+39 08 13.202
Kitab, USSR	+ 66 52 51	+39 08 01.850
Mizusawa, Japan	+141 07 51	+39 08 03.602
Ukiah, USA	-123 12 35	+39 08 12.096

The advantage of having stations located at nearly the same latitude seems obvious. All stations can use the same star program and, having adopted a uniform method of observation and reduction, the derived coordinates of the pole should be free of errors in star positions.

The exact method of reduction shall not be given here. An outline can be found in [Markowitz, 1961, pp. 29-39], and details in [Yumi, 1964 and 1965].

It shall suffice to say that over a period of about six years the periodic motions of the pole average out. One of the programs of the IPMS determines the position of the pole from the observational data accumulated over six years. This position is usually referred to as the mean pole of the epoch. The fact, that consecutive determinations of the mean pole of the epoch showed a displacement of the mean pole of 0".003 to 0".006 per year in the direction of about 55° west longitude has led to much debate on the question of the secular motion of the pole.

The apparent secular motion of the pole was, and by some authors still is, attributed to various causes, such as errors in star positions, errors in scale values of the micrometer, changes and inconsistancies in the star program, and possible horizontal displacements of one or more of the observing stations.

This disbelief led to much confusion in the definition of the mean pole. Consecutive directors of the ILS have changed the mean coordinates of the ILS stations to accomodate the apparent secular motion of the pole [Stoyko, 1964b, p. 42].

In recent years the secular motion of the mean pole has been proven, and in addition, a random motion of the mean pole appears now very likely.

Wm. Markowitz, who contributed greatly to the determination of the secular motion of the pole, gives the following equations for the motion of the mean pole [Markowitz, 1960c, p. 350].

The secular motion is

$$\begin{aligned} x_p &= -\,0''.018 + 0''.0016\ (t-1900), \\ y_p &= +\,0''.014 + 0''.0028\ (t-1900), \end{aligned} \tag{4.20}$$

and the random motion (libration) is

$$\begin{aligned} x_e &= +\,0''.012 \quad \cos 15^\circ\ (t-1902)\ , \\ y_e &= -\,0''.019 \quad \cos 15^\circ\ (t-1902)\ , \end{aligned} \tag{4.21}$$

where t is the epoch.

Analyzing accumulated ILS data for the period 1900-1959, Markowitz found that the secular motion is 0".0032 per year along the meridian 60° W, and the libration with amplitude 0".022 takes place along the meridian 122° W or 58° E, in a period of 24 years. Results of other investigators are given in Table 4.2.

Table 4.2

Secular motion of the mean pole from ILS observations*

Investigator	Interval	Rate per year	Direction of motion,
B. Wanach	1900-1915	0".003	-55°
W. D. Lambert	1900-1917	0.0048	-[illegible]
W. D. Lambert	1900-1918	0.0066	-81
H. Mahnkopf	1900-1922.7	0.0051	-62
H. Kimura	1900-1923	0.0058	-57
B. Wanach	1900-1925	0.0047	-42
N. Sekiguchi	1922.7-1935	0.0103	-91
A. I. Orlov	1900-1950	0.0042	-69
Wm. Markowitz	1900-1959	0.0032	-60

* reproduced from [Markowitz, 1960c, p. 342].

The question of the epoch to which the mean adopted latitudes, $\bar{\Phi}^i_m$, should refer, hence the origin of the polar motion, was settled by the general assembly of the International Union of Geodesy and Geophysics, at Helsinki, in 1960. It was decided that the mean pole of the epoch 1900-1905 shall be adopted as the origin. This origin is usually called the new system 1900-1905 and the mean epoch is 1903. It was further proposed to express the coordinates of the instantaneous pole in the following form [Stoyko, A., 1964b, p. 42]:

$$x = x_0 + x_1$$

$$y = y_0 + y_1$$

where x,y are the coordinates of the instantaneous pole calculated from Equation (4.10), i.e., $\bar{\Phi}^i_m$ refers to epoch 1900-1905, x_0, y_0 are the coordinates of the mean pole of the epoch, i.e., the pole determined from observations over a six year period, and x_1, y_1 are the coordinates of the instantaneous pole, calculated from Equation (4.10) with Φ^i_m equal to the mean latitude of the arbitrary epoch (see Section 4.24).

The coordinates of the mean pole of the epochs 1903 to 1957 are listed in Table 4.3.

Table 4.3

Coordinate of mean pole of epoch

mean epoch	x_0	y_0	z
1903	0."000	0."000	0."000
1909	-0.007	+0.043	-0.001
1915	+0.001	+0.076	-0.028
1927	+0.039	+0.080	-0.117
1932	+0.027	+0.130	-0.116
1938	+0.031	+0.139	-0.037
1952	+0.074	+0.142	-0.064
1957	+0.071	+0.178	

(from [Markowitz, 1960c, p. 349], calculated by G. Cecchini).

A plot of the motion of the instantaneous pole during the period 1960-1964 with respect to the new system 1900-1905, based on IPMS results, is shown in Figure 4.3.

Since 1963, preliminary coordinates of the instantaneous pole are published by the Central Bureau of the IPMS in "Monthly Notes of the International Polar Motion Service". The preliminary coordinates are given in two forms: a monthly mean, and a value at 0.05 year intervals. The data is given for periods about three months in arrears.

Final coordinates, referred to the new system 1900-1905, are published annually in Annual Report of the International Polar Motion Service. The coordinates are given at intervals of 0.05 years and are published for periods about two years in arrears.

It should be noted that data published by the IPMS is obtained from observations at the 5 ILS stations listed in Table 4.1 only, and that the origin of the IPMS data is the new system 1900-1905.

4.24 The Rapid Latitude Service

By definition,

$$UT2 = UTC^i + \Delta\lambda^i + \Delta S ,$$

where i refers to an arbitrary observatory, $\Delta\lambda$ is from Equation (4.15), and ΔS is the seasonal variation correction (see Section 4.31). Thus, it is necessary to know the coordinates of the instantaneous pole to obtain current values of UT2. The ILS results, however, were published with too much delay in the past, and further, changes in the conventional coordinates of the ILS stations introduced breaks in the UT2 time scale.

To avoid these problems, the RLS was established for determining and distributing polar motion corrections to observed time. The general assembly of the IAU at Moscow in 1958, decided that the RLS should use the mean pole of the current epoch as origin for the calculation of the coordinates of the instantaneous pole [Stoyko, 1964b].

This means that time corrections due to the motion of the pole are based only on the periodic motions, i.e., Chandler terms, and that secular motion is neglected. The coordinates published by the RLS since January 1, 1959 are based on the mean pole of the epoch. In

Bureau International de l'Heure

Circulaire n° 117 (20 décembre 1965)

Coordonnées du pôle instantané rapportées au pôle moyen de l'époque et corrections de longitude TU1-TU0, à 0^hTU.

Tableau B. Valeurs interpolées

Date 1965	J.J. 2439	Interpol. x	y	Al	BA	BG	Bl	Bo	Bs	Bu	G	H	HP
Nov. 15	079.5	+0″.198	-0″.077	+0^s.0033	- 96	+ 1	+ 2	+ 14	+ 40	- 12	+ 62	+ 38	+ 37
25	089.5	+ 187	- 102	+ 46	- 97	+ 25	+ 20	+ 37	+ 59	+ 6	+ 83	+ 62	+ 53
Déc. 5	099.5	+ 170	- 126	+ 59	- 97	+ 49	+ 39	+ 61	+ 77	+ 25	+102	+ 85	+ 69

1965	Ir	Kh	L	LP	M	Mi	MP	MS	Mz	N	Nk	Nm	O	Pa
Nov. 15	-182	- 44	- 39	- 97	- 59	+ 30	- 88	+ 79	- 99	+ 38	- 28	-178	+143	+ 53
25	-178	- 24	- 8	- 98	- 33	+ 48	- 90	+ 86	-107	+ 56	- 8	-165	+139	+ 72
Déc. 5	-169	+ 1	+ 26	- 98	- 4	+ 65	- 87	+ 92	-111	+ 74	+ 12	-146	+132	+ 91

1965	Pr	Pt	Pu	Rc	Rg	RJ	SC	SF	Ta	To	U	VJ	W	Zi
Nov. 15	+ 21	+ 26	- 38	+ 67	- 10	- 54	- 93	+ 48	- 92	- 90	+ 51	+ 1	+113	- 84
25	+ 42	+ 49	- 7	+ 64	+ 17	- 57	- 92	+ 60	- 81	- 93	+ 71	+ 24	+110	- 87
Déc. 5	+ 63	+ 73	+ 26	+ 61	+ 47	- 59	- 89	+ 71	- 67	- 99	+ 92	+ 49	+104	- 86

Tableau C. Valeurs extrapolées

Date 1966	J.J. 2439	Extrapol. x	y	Ba	Bl	Bo	G	H	Ir	Kh	L	M	MS	Mz
Fév. 13	169.5	-0″.018	-0″.161	-0^s.003	+10	+13	+13	+14	- 2	+11	+17	+13	+ 7	- 6
23	179.5	- 45	- 152	- 2	+10	+14	+12	+15	0	+12	+18	+15	+ 5	- 4
Mars 5	189.5	- 72	- 137	- 3	+10	+13	+11	+13	+ 3	+12	+18	+15	+ 4	- 4

1966	N	Nk	O	Pa	Pr	Pt	Rc	Rg	RJ	SF	Ta	To	U	W	Zi
Fév. 13	+11	+11	+ 2	+12	+12	+14	0	+16	- 3	+ 8	+ 4	- 5	+13	+ 1	- 2
23	+11	+11	0	+12	+13	+14	0	+16	- 2	+ 7	+ 5	- 5	+12	0	- 1
Mars 5	+11	+11	- 3	+10	+12	+13	- 1	+16	- 2	+ 7	+ 7	- 3	+11	- 2	- 1

Les coordonnées du pôle sont calculées d'après les données des 33 stations suivantes : ALGER, BELGRADE, BESANCON, BLAGOVESTCHENSK, BOROWIEC, CARLOFORTE, DRESDE, ENGELHARDT, GAITHERSBURG, GORKI, GREENWICH, HAMBOURG Hydrogr., HAUTE-PROVENCE, IRKOUTSK Astr., KITAB (2 instr.) LA PLATA, MILAN, MIZUSAWA (2 instr.), MONT-STROMLO, NEUCHATEL, OTTAWA, PARIS, PECNY, POLTAVA (2instr.), POTSDAM, POULKOVO, QUITO, RICHMOND, TOKYO, TURKU-TUORLA, UKIAH, VARSOVIE-JOSEFOSLAW, WASHINGTON.

Figure 4.2: RLS coordinates of the instantaneous pole referred to the mean pole of the epoch, and values UT1 - UT0 at 0^h UT. Abbreviations are identified on Figure 6.7. J.J. stands for Julian Date.

other words, the coordinates x_0 and y_0 of Equation (4.22) are equal to zero since that date; thus $x = x_1$ and $y = y_1$.

The pole used since the above date by the RLS has the following coordinates in the new system 1900-1905 [Markowitz, 1961, p. 36]:

$$x_{RLS} = +0\overset{''}{.}031$$
$$y_{RLS} = +0\overset{''}{.}159 \ .$$

In the above publication, Markowitz strongly proposes that the secular motions should be considered in time corrections, and that the RLS pole ought to be the same as the IPMS pole. This seems desirable if one considers that the secular motion since 1900 has about the same magnitude as the periodic variations during one Chandler cycle. The change has not been made as of yet.

Coordinates of the instantaneous pole are calculated by the RLS from observational results of 33 stations, including the ILS stations. Most of the stations are observatories which participate in the determination of the mean observatory (see Section 6.521). The coordinates are calculated from Equations (4.10) and (4.16), or a combination of the two. Publication of the data is made in two forms through the BIH.

Table B, Figure 4.2, gives interpolated coordinates x, y of the instantaneous pole with respect to the mean pole of the epoch, tabulated for 0^hUT at ten day intervals. The period covered is usually about one month in arrears of the date of publication.

Table C, Figure 4.2, gives extrapolated coordinates of the instantaneous pole for periods of about two months ahead of the date of publication.

Both tables contain the values $\Delta\lambda =$ UT1 - UT0 for each of the time services participating in the determination of the mean observatory. The interpolated values are used to determine final corrections to observed time, the extrapolated values are used for preliminary corrections.

Thus, final values of UT1 and UT2 are based, among other corrections, on the interpolated values of the instantaneous coordinates of the pole, as determined by the RLS [Markowitz, 1965].

Corrections to observed time and radio time signals are more fully discussed in Section 6.5.

4.25 Comparison between IPMS and RLS coordinates

A comparison between IPMS and RLS coordinates of the instantaneous pole is shown in Figure 4.3. The plot of the IPMS pole is taken from [Yumi, 1965]. The path for the RLS pole has been plotted from data contained in Table B of the BIH circulars Nos. 99 to 106. The RLS coordinates have been reduced to the new system 1900-1905 using the values given by [Markowitz, 1961, p. 36] mentioned above.

Table 4.4 shows the differences between IPMS and RLS results for 1963. The IPMS data is taken from [Yumi, 1965, p. 98] the RLS data was obtained by interpolation in Table IV of Bulletin Horaire, Série H, Nos. 1 through 6, reduced to the IPMS pole of 1900-1905.

It should be noted that the RLS coordinates listed in Table 4.4 have been determined from observations at about 33 observatories. The IPMS coordinates have been determined from observations at the five ILS stations. The IPMS values have been read from smoothed curves. The last figure in the Δx and Δy columns of Table 4.4 should be regarded as approximate.

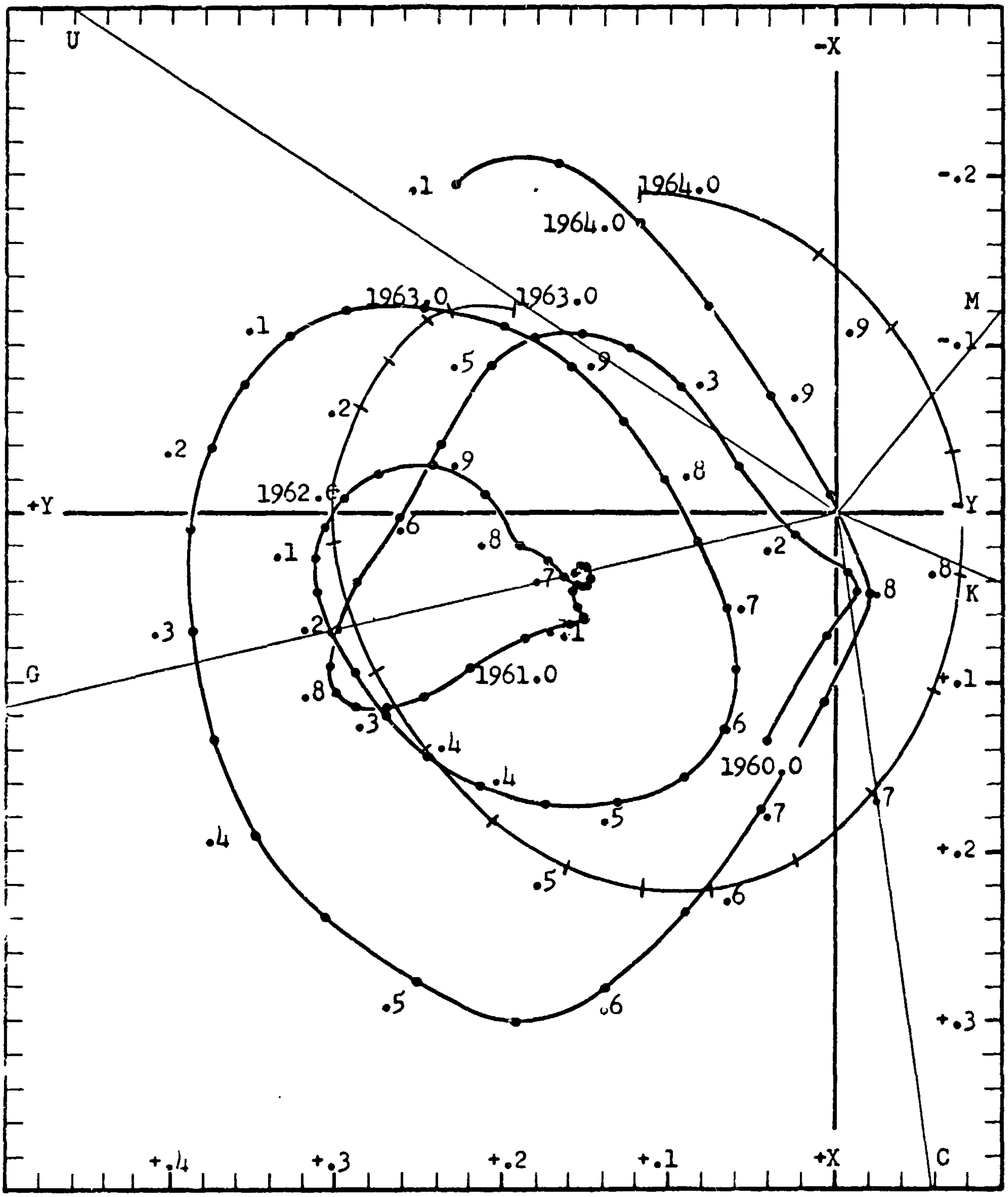


Figure 4.3: Position of the instantaneous pole at 0.5 year intervals.

Results obtained by IPMS for period 1960.0 to 1964.1 .

Results obtained by RLS for period 1963.0 to 1964.0.

Letters indicate the directions to the five ILS stations.

Table 4.4

Comparison of published IPMS and RLS coordinates of the instantaneous pole

Besselian year	IPMS		RLS		IRMS - RLS	
	x	y	x	y	Δx	Δy
1963.00	-0".121	+0".248	-0".123	+0".189	+0".002	+0".059
.05	-0.119	+0.295	-0.118	+0.225	-0.001	+0.070
.10	-0.105	+0.329	-0.118	+0.252	+0.013	+0.077
.15	-0.076	+0.356	-0.095	+0.272	+0.019	+0.084
.20	-0.038	+0.376	-0.062	+0.288	+0.024	+0.088
.25	+0.009	+0.388	-0.012	+0.298	+0.021	+0.090
.30	+0.070	+0.387	+0.018	+0.297	+0.052	+0.090
.35	+0.134	+0.375	+0.098	+0.282	+0.036	+0.093
.40	+0.191	+0.349	+0.144	+0.251	+0.047	+0.098
.45	+0.239	+0.307	+0.184	+0.206	+0.055	+0.101
.50	+0.274	+0.251	+0.214	+0.160	+0.060	+0.091
.55	+0.301	+0.193	+0.231	+0.115	+0.070	+0.078
.60	+0.281	+0.139	+0.231	+0.070	+0.050	+0.069
.65	+0.237	+0.091	+0.213	+0.022	+0.024	+0.069
.70	+0.176	+0.046	+0.172	-0.025	+0.004	+0.071
.75	+0.112	+0.008	+0.113	-0.061	-0.001	+0.069
.80	+0.048	-0.020	+0.038	-0.078	+0.010	+0.058
.85	-0.011	+0.005	-0.039	-0.068	+0.028	+0.073
.90	-0.069	+0.041	-0.108	-0.036	+0.039	+0.077
.95	-0.122	+0.078	-0.157	+0.010	+0.035	+0.068

In spite of the large differences both publications list the data as coordinates of the instantaneous pole. This is just an indication of how difficult it is to determine the absolute position of the pole.

4.3 Variations in the Earth's Rotation Speed

Similarly to the discussion of polar motion we will not enter into theories concerning the causes of variations in the rotation speed of the Earth, but accept it as fact.

Three types of variations in the rotation speed of the Earth have been proven conclusively: a gradual secular retardation; periodic variations with annual, semi-annual, 13.6, and 27.6 day periods; and irregular variations. Only the periodic variations are considered in time corrections.

In generrl, the secular retardation is attributed to tidal friction, especially in shallow seas. It has been determined from analysis of ancient eclipse records and astronomical observations since the 17th century. The effect of the secular retardation is about $4^{s}.5 \times 10^{-8}$ per day, or $0^{s}.0016$ per century [Mühlig, 1960, p. 51].

Irregular variations are the most mysterious of the changes in rotation speed. They are usually thought to be caused by unknown phenomena within the Earth. It was formerly believed that sudden changes in rotation speed occur. Since about 1950, however, it is thought that the irregular changes are the result of accumulated, small random changes, and that abrupt changes do not occur. Irregular variations are determined from comparisons of UT2 against ET or AT, after effects of secular and periodic changes have been removed. The U. S. Naval Observatory determined, from comparisons of UT2 with caesium standards, that a practically uniform deceleration of the Earth's rotation took place between September 1955 and January 1958. The deceleration amounted to an increase in the length of the day of 0.43 milliseconds per year for the period under study [Markowitz, 1958, p. 30].

Results of a longer comparison interval showed a deceleration from June 1955 until about September 1957, an acceleration until about January 1962, and a deceleration until about 1964.25 [Markowitz et al., 1964, pp. 154-155]. A graphical representation of this investigation is shown in Figure 4.4. The figure shows the monthly means of UT2 - A.1, corrected for a linear term, based on observations for UT2 at the USNO and its substation Richmond.

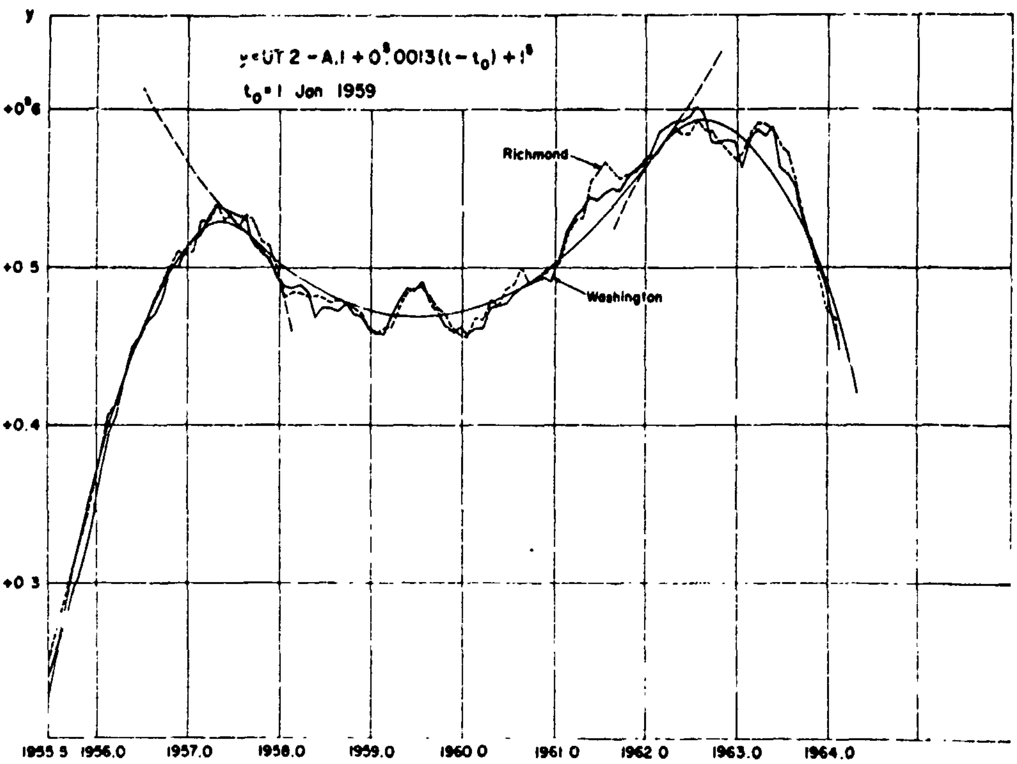


Figure 4.4: Monthly means of UT2 - A.1, corrected for a linear term, derived by Wm. Markowitz and R.G. Hall, March 1964. From [Markowitz et al., 1964, p. 154].

4.31 The seasonal variation

The annual and semi-annual periodic variations in the rotation speed of the Earth are, collectively called seasonal variation.

Part of the annual seasonal variation is due to earth tides induced by the attraction of the sun. The resultant change in the figure of the Earth causes a change in the moment of inertia. Since the angular momentum is constant, a change in rotation speed occurs.

Another annual part, which cannot be explained through gravitational theory appears to be mainly due to winds. The observed semi-annual, non-gravitational variation has not yet been satisfactorily explained. The amplitude of the semi-annual term is about 9 milliseconds [Markowitz, 1958, p. 29].

The seasonal variation was first reliably determined by N. Stoyko in 1937, at the BIH. He used a combination of quartz-crystal and Shortt clocks and found from an analysis of time observations, that the amplitude of the seasonal variation was about $\pm 0^{s}.060$ during the course of a year. Later investigators found similar results which led to the assumption that the seasonal variations are repetitive.

The correction for the annual and semi-annual terms, which comprise the seasonal variation, may be written in the form [Markowitz, 1958, p. 28],

$$\Delta S = a \sin 2\pi t + b \cos 2\pi t + c \sin 4\pi t + d \cos 4\pi t, \qquad (4.23)$$

where a,b,c, and d are empirical constants, and t is the fraction of the year, taken as zero at 12^{h}UT on January 1.

The coefficients are determined from observed differences between astronomical observations for UT2 and precision clocks, nowadays atomic clocks.

The BIH has been instructed by the general assembly of the IAU, at Dublin in 1955, to determine and publish in advance the coefficients so that they may be used by all coordinated time services in the determination of UT2. The coefficients adopted since 1956 are listed in Table 4.5.

Table 4.5

Coefficients for seasonal variation adopted by the BIH since 1956

Coefficient / years	a	b	c	d
1956-1961	$+0^{s}.022$	$-0^{s}.017$	$-0^{s}.007$	$+0^{s}.006$
1962-	+0.022	-0.012	-0.006	+0.007

Tableau A

Corrections ΔT_s qu'il faut ajouter au temps universel pour l'affranchir des variations à courtes périodes de la rotation terrestre. Corrections données pour 0^hTU, en $0^s.0001$.

Date 1966		J.J. 2439	ΔT_s en $0^s.0001$
Jan.	4	129.5	- 46
	9	134.5	- 37
	14	139.5	- 30
	19	144.5	- 24
	24	149.5	- 18
	29	154.5	- 13
Fév.	3	159.5	- 7
	8	164.5	0
	13	169.5	+ 7
	18	174.5	+ 16
	23	179.5	+ 27
	28	184.5	+ 38
Mars	5	189.5	+ 50
	10	194.5	+ 64
	15	199.5	+ 80
	20	204.5	+ 98
	25	209.5	+117
	30	214.5	+137
Avril	4	219.5	+157
	9	224.5	+178
	14	229.5	+199
	19	234.5	+219
	24	239.5	+238
	29	244.5	+255
Mai	4	249.5	+270
	9	254.5	+284
	14	259.5	+294
	19	264.5	+301
	24	269.5	+305
	29	274.5	+304
Juin	3	279.5	+300
	8	284.5	+291
	13	289.5	+278
	18	294.5	+262
	23	299.5	+241
	28	304.5	+216
Juil.	3	309.5	+188
	8	314.5	+158
	13	319.5	+125
	18	324.5	+ 90

Date 1966		J.J. 2439	ΔT_s en $0^s.0001$
Juil.	23	329.5	+ 54
	28	334.5	+ 16
Août	2	339.5	- 21
	7	344.5	- 57
	12	349.5	- 92
	17	354.5	-126
	22	359.5	-159
	27	364.5	-187
Sept.	1	369.5	-213
	6	374.5	-235
	11	379.5	-254
	16	384.5	-269
	21	389.5	-279
	26	394.5	-287
Oct.	1	399.5	-290
	6	404.5	-288
	11	409.5	-284
	16	414.5	-276
	21	419.5	-267
	26	424.5	-254
	31	429.5	-240
Nov.	5	434.5	-223
	10	439.5	-206
	15	444.5	-188
	20	449.5	-170
	25	454.5	-152
	30	459.5	-135
Déc.	5	464.5	-119
	10	469.5	-104
	15	474.5	- 89
	20	479.5	- 76
	25	484.5	- 65
	30	489.5	- 55
	35	494.5	- 46

Note : ΔT_s a été calculé par la même formule depuis 1962 inclus.

Figure 4.5: Predicted seasonal variation for 1966. ΔT_s = ΔS of text; J.J. stands for Julian Date.

The BIH publishes the values ΔS = UT2 - UT1 at 5 day intervals for the whole year in its Table A (Figure 4.5) in advance. The first issue of the Bull. Hor. each year contains the same table (see Section 6.52). The published values are calculated from Equation (4.23). The adopted coefficients remain unchanged throughout the whole year. This means that the correction for the seasonal variation is based on predicted coefficients.

Contrary to the corrections for the motion of the pole, which is unique for each station, the correction for seasonal variation, ΔS, is the same to all stations.

4.32 Lunar tidal variations

The periodic variations of 13.66 and 27.55 day periods are due to earth tides induced by the Moon, which cause variations in the rotation speed in the same manner as the Sun does.

The 13.66 day term is due to the varying declination of the Moon, the 27.55 day term is due to the varying distance of the Moon from the Earth. The effects of these lunar terms on the rotation of the Earth have been determined theoretically and have been confirmed by PZT observations at the USNO. A correction of $(+0^s.15 \pm 0^s.03) \sin \Omega$, where Ω is the mean longitude of the Moon's node, is required to remove these terms [Markowitz, 1962b, p. 242].

In practical time determination the lunar terms are eliminated by smoothing the observations over a period of about two months [Essen et al., 1958, p. 1054].

4.4 The Non-Uniformity of UT 2

There are about 40 observatories in the world today which determine

UT2. Consistency in the determination is assured by adherence to international agreements. Each observatory calculates UT2 according to the, by now, familiar equation

$$UT2 = UT0^{i} + \Delta\lambda^{i} + \Delta S$$

Considering now the practice of smoothing the observations over several months to cancel the lunar tidal terms, one can say, that in effect UT2 represents the mean rotation of the Earth when freed of periodic variations.

UT2 determined at a particular observatory is, however, still non-uniform.

Quantities that are neglected have been pointed out in this chapter, e.g., secular motion of the pole, irregular variations in rotation speed, etc. However, even if eventually corrections for observed seasonal variation and other observable phenomena would be applied, UT2 would still depart from a uniform time system such as ephemeris time. The continuous long term divergences are clearly indicated by the quantity ΔT = ET-UT.

A further point to consider is the fact that each observatory, theoretically and practically, determines its own UT2 system, owing to the dependence of the UT calculations on adopted, conventional longitudes. The BIH smoothes out the discrepancies between UT2 determinations by forming a so-called mean observatory and therewith an international or truly universal time. The formation of the mean observatory will be discussed in Section 6.521, after we have dealt with the distribution of time through radio broadcasts.

V. DISTRIBUTION OF PRECISE TIME AND FREQUENCY

5.1 Introduction

Having dealt with the determination of the epoch of time by astronomical methods in observatories, the various time and frequency standards keeping time on a uniform basis, and the variations in rotational time, it is appropriate to discuss the means that disseminate precise time and frequency to all users. These means are worldwide standard time and frequency radio broadcasts and they, and their synchronization, are the subject of this chapter.

The term standard time used in the literature and adhered to here in connection with radio time broadcasts should not be confused with the time assigned to a time zone, e.g., eastern standard time. In the present context, standard time refers to a time kept by some primary time standard, e.g., such as the master clock of the USNO. The epoch associated with standard time in the present meaning may differ from universal time by an integral number of hours, but this is not a condition. In fact, it may refer to either universal or atomic time when dealing with broadcast time.

Radio broadcasts of precise time and frequency from certain standards laboratories, e.g., the NBS, usually provide standard frequency with or without standard time signals that provide both epoch and time interval.

Radio time and frequency broadcasts provide the reference for comparisons of local time and frequency standards to an accepted primary standard. The geodesist is primarily concerned with the exact epoch of an observation. For this reason time signal broadcasts that provide, after certain corrections, the epoch of UT2 will be treated more extensively than pure frequency transmissions.

Several methods of time comparisons, i.e., comparisons of locally kept time with a radio time source, and corrections to the received time in order to arrive at UT2 or atomic time (in lieu of ephemeris time), will be dealt with separately in Chapter VI.

Standard frequency broadcasts without time information will be mentioned only briefly. They are mainly for laboratory use, for calibration of transmitters at radio stations, and for navigation. They are of general interest in worldwide synchronization of primary time and frequency standards. The geodesist may also wish to use them but only in special cases, e.g., at satellite tracking stations, when a frequency standard is used as the basis for precise timing. In what follows, the close relationship between time and frequency ought to be borne in mind.

Note that we are not concerned with the theory or techniques of radio transmissions but with the transmitted information that aids the geodesist.

5.2 International Agreements Concerning Time Signal Broadcasts

The present day radio communications network has assumed immense proportions with the result, that radio time signals can be received practically anywhere on Earth from one or more radio stations.

Chaos would result if not a high degree of international coordination in the mode of time signal transmission would have been established. The coordinating agency is again primarily the BIH.

5.21 Frequency offsets and step adjustments in phase

The fundamental unit of time, the second, is by definition the second of atomic time; it is the interval needed for 9 192 631 770 oscillations of the caesium-133 atom (see Section 1.22). Owing chiefly to the variable rate of the Earth's rotation the intervals of UT2 and AT diverge.

Practically all standard time stations transmit a time, designated UTC. This time system may be viewed as a predicted UT2. It is obtained by applying corrections for predicted seasonal variation and extrapolated polar motion to observed UT0. The difference between the epoch of UTC and UT2 is usually less than $\pm$ 0.1 second. The proximity of UTC and UT2 is obtained by applying two different kinds of adjustments to the transmitted time signals: (1) frequency offsets, and (2) step adjustments in phase.

(1) The fundamental frequency is that of the caesium atom. Therefore, the transmission frequencies of standard time stations must be offset from the basic frequency, which amounts to an interval conversion.

By international agreement the frequency emitted is

$$F = F_o \ (1+s), \tag{5.1}$$

where F is the frequency emitted, F_o is the nominal frequency of caesium and s is a fixed offset that remains unchanged throughout the whole year.

The frequency offset s is

$$s = \frac{\Delta F}{F_o} = 50n \times 10^{-10}, \tag{5.2}$$

where n is a positive or negative integer, or zero.

The frequency offset as defined above was recommended by the XIIth general assembly of the IAU at Hamburg in 1964 [IAU, 1964], and was confirmed by the International Radio Consultative Committee at Monaco in 1965.

The amount of offset, i.e., the value of n, is fixed by the BIH for a year in advance, and it is based on comparisons between UT2 and AT during the preceding year.

During 1965 the frequency offset was -150×10^{-10}, for 1966 it is -300×10^{-10} according to a BIH Circular, dated September 21, 1965.

It follows that

$$\text{transmission interval} = (1 + \frac{\Delta F}{F_0}) \times \text{atomic interval} . \qquad (5.3)$$

(2) Owing to unpredictable changes in UT2, the adopted value of $\Delta F/F_0$ may not suffice to keep the epoch of UTC in step with UT2. In order to retain a close agreement, step adjustments in phase are made.

The amount of adjustment and manner in which it is applied was decided upon by the two meetings mentioned in connection with the frequency offset. By international agreement the step adjustment is exactly ± 100 milliseconds, applied at 0^hUT of the first day of a month, when required. The need of an adjustment is determined by the BIH upon consultation with major time observatories. Adjustments are announced by the BIH 45 days in advance to all transmitting stations.

It should be noted that the step adjustment in phase does not change the transmission frequency. It is equivalent to advancing or retarding the transmission clocks by 100 milliseconds, depending on the sign of the adjustment.

The total effect of the adjustments in phase and the frequency offset is that the maximum difference between UT2 and UTC is about ± 0.1 second.

5.22 Definition of a coordinated station

In the following sections we will use the expressions "coordinated" and "non-coordinated" stations. According to [BIH, 1965, p. 2] a coordinated station is one whose time signal transmissions fulfills Equation (5.3), and where step adjustments are applied so that

$$|UT2 - UTC| < 100 \text{ milliseconds}. \qquad (5.4)$$

Non-coordinated stations are those whose transmissions of time signals do not fulfill Equations (5.3) and (5.4)

5.23 Internationally accepted types of radio time signals

There is still a conspicuous absence of uniformity in the mode of time signal transmissions, although the IAU recommended in 1955 that the so-called English system shall be used without exception [Hydrographic Department, Admiralty, 1958, p. 16].

The major systems in use are the following: (1) the English system; (2) the modified rhythmic system; (3) the international ONOGO system; and (4) the technical broadcast system. These systems are briefly described below. Additional information may be found in the above publication.

(1) in the English system time signals are radiated for five minutes preceeding the hour, i.e., from 55^{m} to 60^{m}. Each second is marked by a $0\overset{s}{.}1$ tick. At the minute, the tick is lengthened to $0\overset{s}{.}6$. The commencement of each tick is the reference point. The last five seconds of each minute are graphically represented by

55 56 57 58 59 60 1

(2) The modified rhythmic system consists of 306 signals emitted in 300 seconds of mean time. Transmission is usually made for five minutes only, either before or after the hour.

In each five minute period, signals number 1, 62, 123, 184, 245, and 306 are single dashes of $0\overset{s}{.}4$ duration and commence at exact minutes. Each dash is followed by 60 ticks of $0\overset{s}{.}1$ duration. The instants of commencement of tick or dash are evenly spaced at intervals of 60/61 parts of one second of mean time.

The signals produce a vernier effect with the seconds breaks of a mean time or sidereal time chronometer. With the latter coincidences occur at intervals of 72 seconds of mean time.

(3) the international ONOGO system has become almost obsolete. The name is derived from the sequence of Morse code letters transmitted during three minutes preceding the hour.

The sequence of transmission is as indicated graphically in Figure 5.1. Each dash is of one second duration, followed by one second of silence, each dot is of $0^s.25$ duration. The preparatory signals from $57^m\ 00^s$ to $57^m\ 49^s$ are not time signals. In the modified ONOGO system the letter O is replaced by a dot marking each second.

Time	Signal representation	Letter
$57^m 00^s$ - $57^m 40^s$	——— • • ——— ——— • • etc.	X
57 55 - 58 00	55^s 56^s 57^s 58^s 59^s 60^s	O
58 08 - 58 10	08 09 10	N
58 18 - 58 20	18 19 20	N
• • • •	• • •	•
• • • •	• • •	•
58 48 - 58 50	48 49 50	N
58 55 - 59 00	55 56 57 58 59 60	O
59 06 - 59 10	06 07 08 09 10	G
59 16 - 59 20	16 17 18 19 20	G
• • • •	• • • • •	•
• • • •	• • • • •	•
59 46 - 59 50	46 47 48 49 50	G
59 55 - 00 00	55 56 57 58 59 60	O

Figure 5.1: The international ONOGO system of time signal treansmission. In the modified ONOGO system the letter O is replaced by a dot marking each second.

(4) the so-called technical broadcast system is fully described in Section 5.311. It is typically represented by the standard time stations WWV and WWVH.

The superiority of this system is unchallenged, and it is the system that satisfied the requirements of geodetic astronomy best, because time signals are emitted continuously.

5.3 Standard Time and Frequency Broadcasts

Every major country has its own service broadcasting standard time and frequency primarily for the regulation of the ever expanding radio communications and telegraph networks, and for purposes of safe air and sea navigation.

The United States time and frequency standards shall serve as a representative example of a time and frequency service, although their reliability and precision is above average. Transmitting stations of internationally located time and frequency services are listed in Tables 5.4 and 5.5 and are depicted in Figure 5.5.

In the United States, the NBS and the USNO broadcast standard times and frequencies from several stations.

Transmissions from NBS stations are based on the United States Frequency Standard (USFS) and those of the USNO are based on the A.1 atomic time system. The two standards are in close agreement (see Section 1.21). The broadcasts from NBS stations are the most useful for geodetic purposes and will be described first.

5.31 Broadcasts of the U. S. National Bureau of Standards

Figure 5.1 depicts the evolution of the USFS from an accuracy of $\pm 1 \times 10^{-4}$ in 1920 to an accuracy of $\pm 5 \times 10^{-12}$ in 1964 [Blair and Morgan, 1965, p. 915].

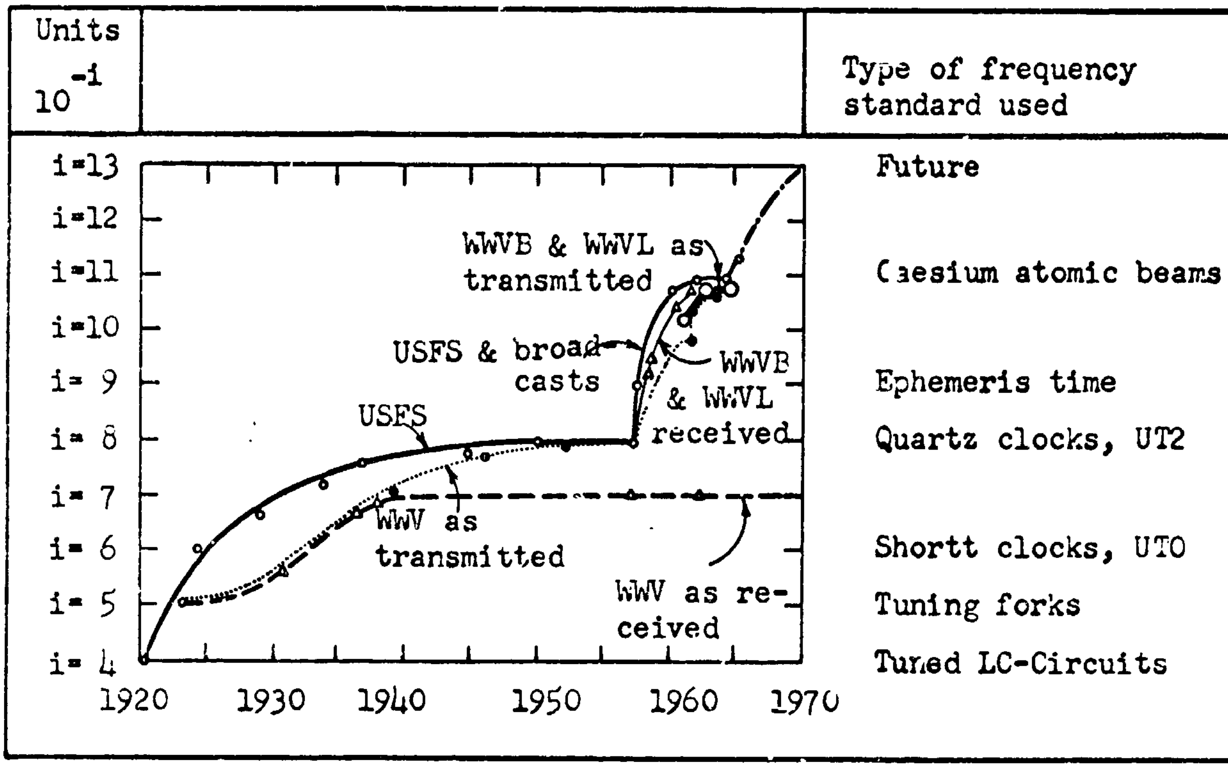


Figure 5.2: The evolution of the USFS. Adapted from Blair and Morgan, 1965 .

The abrupt change in the slope of the curve in 1957 was due to the development of atomic frequency standards. Since 1960 the USFS is based on the operation of two caesium beam resonators, designated NBS-I and NBS-II, respectively. The atomic time associated with the USFS is designated NBS-A (see Section 1.2).

The caesium beams are not operated continuously. Continuity is provided by the U. S. Working Frequency Standard (USWFS), consisting of a group of oscillators; at present four quartz crystal oscillators and one Rb-vapor standard. Time and frequency transmissions from NBS high frequency (HF) stations WWV at Greenbelt, Maryland, and WWVH at Maui, Hawaii, and NBS low and very low frequency (LF and VLF) stations WWVB and WWVL at Ft. Collins, Colorado, are controlled by the USWFS, which is compared daily to the USFS with a precision of $\pm 2 \times 10^{-12}$ [Blair and Morgan, 1965, p. 917]

The entire system depends on the USFS. The Cs-standard is used to control the USWFS, and the frequency dividers and clocks associated with it. Information from USWFS is fed to a phase comparator and transmitter that monitors the WWVB and WWVL transmissions at LF and VLF, respectively. If an error exists between the standard phase and the received phase from WWVB and WWVL, the phase at those stations is automatically corrected via a very high frequency (VHF) link between Boulder and Ft. Collins.

The control of the signals transmitted from WWV and WWVH is performed at present manually. At WWV, both, WWVB and WWVL signals are received by LF and VLF receivers, respectively. At WWVH only WWVL signals are received.

The oscillators controlling the transmission frequencies and time signals at the HF sites are continuously compared with the received LF and VLF signals and phase differences are recorded. The accumulated phase differences are read at exactly 24^h intervals and relayed to the NBS radio laboratory. Since frequency is the rate of change of phase in unit time, the transmission frequency of the HF stations may be calculated from the phase differences in terms of the USFS.

The daily values provide correction data to the oscillators at the HF stations. The WWV broadcast frequency is maintained within $\pm 5 \times 10^{-11}$ from nominal, that of WWVH within $\pm 5 \times 10^{-10}$ of nominal. (Nominal of offset HF frequency, not USFS.)

To assure that no systematic errors enter into the system the NBS compares the transmitting station clocks with the NBS-A time scale by means of a precise portable clock. The whole set-up shows that broadcasts from all NBS stations are traceable to the USFS.

The information contained in the NBS broadcasts is described in

Sections 5.311 and 5.312. The data is based on [NBS, 1965] which is revised annually.

Users of WWVB and WWVL may obtain current schedules and relevant information by writing: National Bureau of Standards,
Frequency-Time Broadcast Services 251.02,
Boulder, Colorado.

5.311 Transmissions from NBS stations WWV and WWVH

Transmissions from these stations are utilized most often in geodetic work. They provide the following information: (1) standard radio frequencies; (2) standard audio frequencies; (3) standard musical pitch; (4) standard time intervals; (5) time signals; (6) corrections to arrive at a close approximation to UT2; (7) propagation forecasts (WWV only); and (8) geophysical alerts.

(1) standard radio frequencies are broadcast on 2.5, 5, 10, 15, and 25 MHz from WWV and on 2.5, 5, 10, and 15 MHz from WWVH. The broadcasts are continuous through 24 hours, except for silent periods. The silent period of WWV commences at 45 minutes (plus 0 to 15 seconds) and ends at 49 minutes after each hour; that of WWVH commences at 15 minutes (plus 0 to 15 seconds) and ends at 19 minutes after each hour.

The carrier and modulation frequencies at WWV and WWVH are derived from precision quartz oscillators with stabilities of 5×10^{-11} and 5×10^{-10} for WWV and WWVH, respectively. Deviations at WWV are nominally less than 1×10^{-11} from day to day.

Changes in the propagation medium (causing Doppler shifts, diurnal shifts, etc.) may result in fluctuations in the carrier frequencies as received, which may be much greater than the uncertainties stated above.

The oscillators generating the HF transmission frequencies are intentionally offset from the USFS as described in Section 5.21.

The frequency offset is given in international Morse code during the last half of the 59th minute each hour by WWV, and during the first half of the 59th minute of each hour by WWVH. The code for 1966 will read M300, following the voice announcement.

Corrections to the transmitted frequencies are continuously determined with respect to the USFS and are published monthly in "Proceedings of the Institute of Electrical and Electronics Engineers (IEEE)" under the heading "Standard Time and Frequency Notices."

(2) standard audio frequencies are broadcast on each carrier frequency at both stations. The audio frequencies are interrupted 40 milliseconds for each seconds pulse. For further details the reader is referred to [NBS, 1965, p. 2].

(3) standard musical pitch is provided through a 440 Hz modulation for the note A above middle C (see [NBS, 1965, p. 2]).

(4) standard time intervals are given by seconds pulses at precise intervals. Due to the frequency offset mentioned above the time intervals in 1966 are exactly ($1-300 \times 10^{-10}$) times the atomic interval (see Section 1.22). The second pulses are locked to the carrier frequency, e.g., they commence at exact intervals of 5,000,000 cycles of the 5 MHz carrier. They are given by means of double-sideband amplitude-modulation on each carrier frequency. Intervals of one minute are marked by omission of the 59th second pulse of every minute and by commencing each minute with two pulses spaced 0.1 second apart. The first pulse marks the minute.

The two, three, and five minute intervals are synchronized with the second pulses and are marked by the beginning or ending of the periods when audio frequencies are not transmitted.

The pulse duration is five milliseconds. At WWV each pulse consists of 5 cycles of a 1000 Hz frequency, at WWVH each pulse contains 6 cycles of a 1200 Hz frequency. Maximum amplitudes are approximately 995 Hz for WWV and 1194 Hz for WWVH. The audio frequencies are interrupted for 40 msec for each seconds pulse. The pulse begins 10 milliseconds after commencement of the interruption.

(5) time signals transmitted by WWV and WWVH are maintained within $0^{s}.1$ of UT2 (the time of the signal is designated UTC) by retarding or advancing the clocks generating the seconds pulses by 100 milliseconds, as described in Section 5.21.

Station identification and universal time is announced in international Morse code during the first half (WWV) and second half (WWVH) of the 5th, 10th, 15th, etc. minute during the hour, i.e., 12 times per hour. The first two figures give the hour, the last two figures give the minute past the hour, referring to the instant when the tone returns.

Station identification and announcement of Eastern Standard (zone) Time in voice is made at WWV during the second half of each fifth minute during the hour, i.e., 12 times per hour; at WWVH the voice announcement is Hawaiian Standard (zone) Time, made during the first half of each fifth minute during the hour. For example, the voice announcement at WWV at say $5^{h}\ 35^{m}$ UT is in English: National Bureau of Standards, WWV; when the tone returns, Eastern Standard Time will be ten hours, thirty-five minutes.

In addition to the above information WWV broadcasts a time code for one minute commencing at 7, 12, 17, etc. minutes of each hour (except during the silent period). The time code has a higher timing potential than the pulse signals. It is of value when simultaneous observations are made at widely separated stations; the time markers being accurate to about one millisecond.

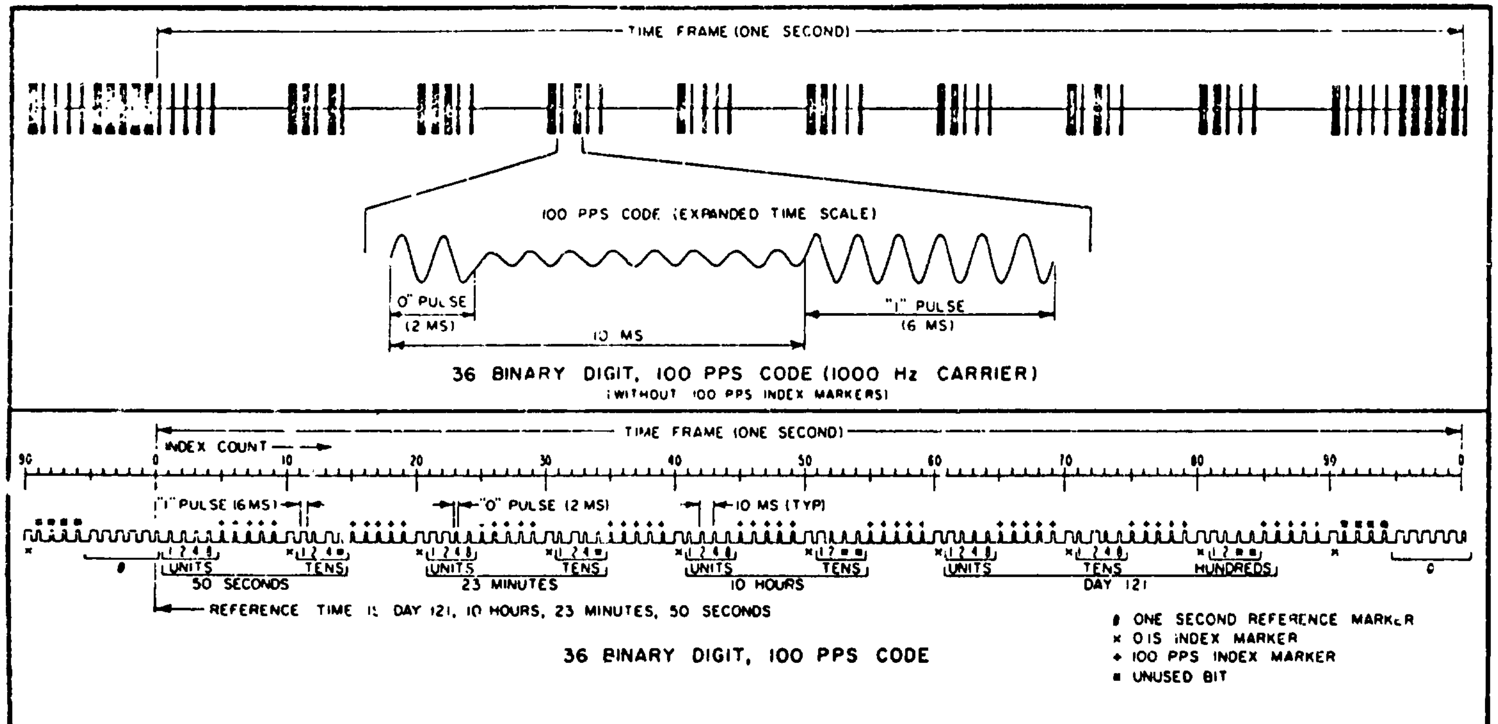
The code format broadcasted is generally known as the NASA 36-Bit Time Code. The code is produced at a 100 pps rate and is carried on a 1000 Hz modulation. It contains the epoch of UTC in seconds, minutes, hours, and day of the year as shown in Figure 5.3a.

The binary-code-decimal (BCD) system is used. A complete time frame is one second containing nine BCD groups as follows: 2 groups for seconds, minutes, and hours, and 3 groups for day of the year. The code digit weighting is 1-2-4-8 for each group, multiplied by 1, 10, or 100, as the case may be. A code-key is shown in Figure 5.3b.

The 1000 Hz modulation is synchronous with the code pulses so that millisecond resolution is possible. A "binary zero" consists of two cycles of 1000 Hz amplitude modulation, and a "binary one" pulse consists of 6 cycles of 1000 Hz amplitude modulation (see enlargement of 100 pps time code in Figure 5.3a).

(6) corrections to the epoch of the signals to arrive at a close approximation to UT2 are given in international Morse code during the second half of the 19th minute of each hour on WWV, and during the second half of the 49th minute on WWVH.

The symbols broadcasted are: UT2, then either AD or SU, followed by a three digit number which represents the correction in milliseconds. The correction is added to the time of the signal if AD is broadcast and subtracted when SU is broadcast.



	Hundreds				Tens				Units			
Bit value	8	4	2	1	8	4	2	1	8	4	2	1
Appearance of Code as broadcast												
In Binary	0	0	1	1	0	0	1	0	0	1	0	1
Read	(2+1)x100				2 x 10				(4+1)x1			
Sum	300 + 20 + 5 = 325											

Figure 5.3a, above: One second time frame of WWV time code.

Figure 5.3b, left: Key to BCD time code.

The corrections are supplied daily by the USNO. New values appear for the first time during the hour following 0^hUT and remain unchanged for the following 24 hours. The probable error of the corrections is supposedly ± 3 milliseconds.

The main reason for these corrections is the fact that the time signals are locked to the carrier frequencies. Thus continuous departure from UT2 is possible. The USNO continuously compares the epoch of transmission of the signals with its master clock. The corrections are the result of an analysis of the recorded departures.

Final corrections to UTC, with a probable error of ±1 millisecond, are issued periodically by the USNO in its Time Signals Bulletins (see Section 6.51).

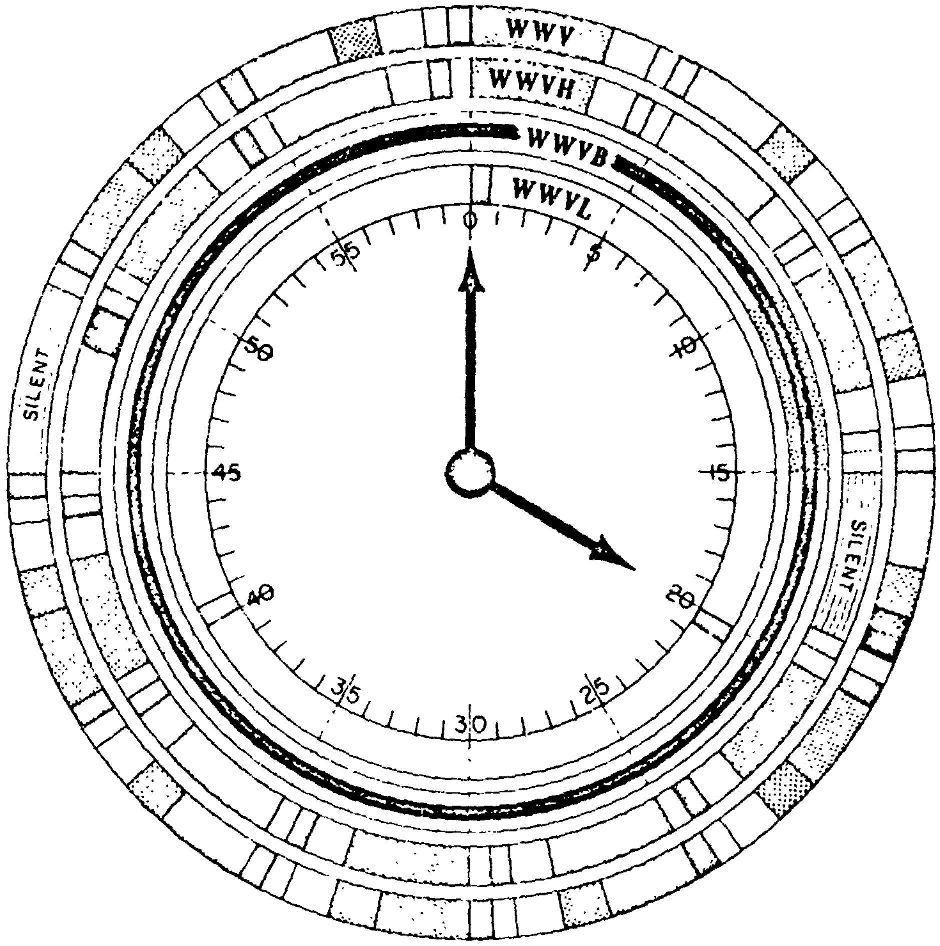
(7) propagation forecasts for radio waves and (8) geophysical alerts are broadcast in international Morse code on all frequencies ((7) at WWV only). For details the reader is referred to [NBS, 1965, p. 5].

5.312 Transmissions from NBS stations WWVB and WWVL

Both stations provide standard radio frequencies. WWVB provides in addition standard time intervals, time signals, and corrections to the signals to arrive at approximate UT2. Stations WWVB and WWVL broadcast on standard radio frequencies of 60 kHz and 20 kHz, respectively. The broadcasts are continuous. The frequencies are normally stable to about $\pm 2 \times 10^{-11}$; deviations from day to day are within $\pm 1 \times 10^{-11}$.

The carrier frequency of WWVL is offset from the USFS by the same amount as WWV and WWVH. Since January 1, 1965 the carrier frequency of WWVB is maintained without offset with respect to the USFS. Thus absolute frequency comparisons may be made using WWVB.

THE HOURLY BROADCAST SCHEDULES
OF WWV, WWVH, WWVB, AND WWVL



SECONDS PULSES - WWV, WWVH - CONTINUOUS EXCEPT FOR 59th SECOND OF EACH MINUTE AND DURING SILENT PERIODS

WWVB - SPECIAL TIME CODE

WWVL - NONE

STATION ANNOUNCEMENT

WWV - MORSE CODE - CALL LETTERS, UNIVERSAL TIME, PROPAGATION FORECAST
VOICE - EASTERN STANDARD TIME
MORSE CODE - FREQUENCY OFFSET (ON THE HOUR ONLY)

WWVH - MORSE CODE - CALL LETTERS, UNIVERSAL TIME,
VOICE - HAWAIIAN STANDARD TIME
MORSE CODE - FREQUENCY OFFSET (ON THE HOUR ONLY)

WWVL - MORSE CODE - CALL LETTERS, FREQUENCY OFFSET

100 PPS 1000 Hz MODULATION WWV TIMING CODE

TONE MODULATION 600 Hz

TONE MODULATION 440 Hz

GEOALERTS

IDENTIFICATION PHASE SHIFT

UT-2 TIME CORRECTION

SPECIAL TIME CODE

REVISED JULY 1965

Figure 5.4

Standard time intervals are marked by second indicators spaced exactly one atomic second apart (strictly speaking one NBS-A second), since there is no frequency offset.

Time signals from WWVB depart from UT2 differently than those of WWV and WWVH. To keep the time transmitted close to UT2, 200 millisecond step adjustments in phase are made at 0^hUT on the first day of a month at the discretion of the NBS.

The time signals are indicated by 60 drops in power of 10 decibels per minute, each drop marking one second. Each minute the following information is given in BCD code: the minute, the hour, the day of the year, and the difference between the time of broadcast and approximate UT2, in milliseconds. The latter information is based on a NBS Circular dated June 23, 1965. A key for deciphering the WWVB time code is given in [Hewlett-Packard, 1965, pp. AIII-1 to AIII-5].

It has to be kept in mind that the time interval derived from WWVB broadcasts is the atomic interval, although the epoch given is close to UT2.

Station identification is given at WWVB and WWVL by international Morse code during the 1st, 21st, and 41st minute of each hour. In addition WWVB identifies by advancing the carrier phase 45° between 10 and 15 minutes after each hour.

The broadcast schedules of WWVB and WWVL are shown in Figure 5.4. That of WWVB is based on a revision to [NBS, 1965] announced in a NBS Circular, dated June 23, 1965.

5.32 Broadcasts controlled by the U. S. Naval Observatory

The USNO is the only agency in the United States which determines time (UT, ET, and A.1). Through its master clock (see Section 3.431) the

USNO controls the time signals broadcast from U. S. Naval radio stations, from the NBS stations WWV and WWVH, and from the U. S. East Coast Loran-C stations, which are operated by the U. S. Coast Guard. In addition, the USNO monitors worldwide time and frequency transmissions for the purpose of time synchronization. It also plays a key role in international time coordination programs (see Section 5.42).

U. S. Naval radio stations, like those of the U. S. Coast Guard are operated chiefly for navigational purposes. Some stations broadcast precise time intervals and epoch in addition to standard frequency, and may be of use to the geodesist.

Broadcast frequencies of U. S. Naval stations (all VLF, but not all HF stations) and U. S. East Coast Loran-C stations are directly related to the system of atomic time, A.1 (see Section 1.22). All frequencies are offset from the atomic standard and step adjustments in phase of 100 milliseconds are made in the manner described in Section 5.21 [Markowitz, 1964a].

5.321 Transmissions from U. S. Naval radio stations

All U. S. Naval radio stations broadcast standard frequencies and time. For the geodesist the HF transmissions and the VLF transmissions of NBA are of interest only. Frequencies and broadcast schedules are listed in Table 5.1.

The VLF stations also broadcast time signals. A note in USNO Time Service Announcement, dated August 5, 1964, shall be quoted:

"Time pulses of high precision are transmitted continuously from NBA. Pulses transmitted from other stations are provided for special tests; these are not time signal pulses."

Table 5.1

U.S. Naval radio stations and HF time broadcast schedules

Call Sign	Location	Frequencies in kHz		Time Broadcasts UT **
		VLF *	HF **	
NAA	Cutler, Maine	17.8		
NBA	Balboa, Canal Zone	24.10	147.85; 5,448.5; 11,080; 17,697.6	$5^h, 10^h, 17^h, 23^h$
NLK/NPG	Jim Creek, Washington	18.6	114.95; 4,010; 6,429.51; 9,277.5; 12,966; 17,055.2; 22,635	NPG at $0^h, 6^h, 12^h, 18^h$
NPM	Lualualei, Hawaii	26.1	131.05; 4,525; 9,050; 13,655; 17,122.4; 22,593	$0^h, 6^h, 12^h, 18^h$
NPN	Guam		484; 4,955; 8,150 13,530; 17,530; 21,760	$0^h, 6^h, 12^h, 18^h$
NSS	Annapolis, Maryland	21.4	122; 162; 5,870; 9,425; 13,575; 17,050; 23,650	$0^h, 2^h, 6^h, 8^h, 12^h$ 18^h

* based on [Markowitz, 1964a]. The VLF of NPM was changed from 19.8 to 26.1 kHz on October 1, 1964, according to USNO Time Service Announcement, dated September 30, 1964.

** based on [BIH, 1965] April 1965 schedule. Time signals are transmitted in the English system (see Section 5.23) for five minutes preceding indicated hours.

Further, it is noted that corrections to the times of broadcast in order to obtain UT2 are published in the USNO Time Signals Bulletins for the following stations only: NBA (all frequencies), NSS (HF only), and NPG (17055 kHz only).

The VLF time and frequency broadcasts from NBA at 24.0 kHz had been suspended during most of the year 1965. A new transmitter has been installed which renewed operation about November 1, 1965 according to USNO Service Announcements, dated February 12, and October 15, 1965, respectively.

Before shut-down, NBA (VLF) transmitted precise time signals (UTC) continuously, except from 12^h to 21^h on Wednesdays. In addition, experimental time signal transmissions were made for several minutes each hour. Station identification and the frequency offset from the Cs-atomic standard were announced in international Morse code several times during each hour.

The day-to-day variation in frequency broadcast from NBA (VLF) was about $\pm 5 \times 10^{-11}$ [Markowitz, 1962a, p. 12].

Broadcast schedules and the mode of time signal transmission from the new VLF (24.0 kHz) transmitter at NBA have, to this writer's knowledge, not yet been published.

U. S. Naval radio stations that may possibly serve the geodesist are included in Table 5.5. Station locations are shown in Figure 5.5.

5.322 Transmissions from Loran-C stations

Loran-C is a pulsed, hyperbolic radio navigational system, operating on a carrier frequency of 100 kHz. Owing to very favorable propagation characteristics (see Section 5.4) Loran-C may eventually be used to disseminate precise time over large distances for synchronization purposes.

A Loran-C chain consists of a master and two or three slave stations. In 1961 the USNO began control of the time pulses broadcast by the master station of the U. S. East Coast Loran-C chain, located at Cape Fear, North Carolina [Markowitz, 1962a, p. 12].

The frequency of the rubidium gas cell oscillator at Cape Fear is synchronized with the master clock of the USNO through monitoring the USNO signal at Cape Fear. The other stations comprising the chain (Table 5.2) monitor the Cape Fear signals. Thus, the emission of time pulses from any one of the Loran-C stations is synchronized with the USNO master clock [Markowitz, 1962a, p. 12-15].

To prevent interference of the pulses, the three slave stations have a fixed emission delay with respect to Cape Fear which is held constant to about 0.1 microsecond (see Table 5.2). The mode of time pulse transmission is according to USNO Time Service Announcement, dated May 25, 1965 as follows:

Effective July 1, 1965, the nominal transmission consists of a group of 8 pulses spaced one millisecond apart. A nineth pulse, not one millisecond from the eighth, identifies the master station. (Blinking of this pulse indicates that the Loran-C system is not operating.) The groups of 8 pulses have a repetition period of 80 milliseconds, thus there are 12.5 repetitions per second.

A once-per-second pulse, two milliseconds before each second of UTC, is transmitted by Cape Fear only. Thus, the sequence of pulses emitted from Cape Fear is:

Once-per-second pulse		
1st pulse of first cycle	at	$59^s.998$ UTC
1st pulse of 1st group of 8	at	0.000
1st pulse of 2nd group of 8	at	0.080
⋮		⋮
1st pulse of 12th group of 8	at	0.960
Once-per-second pulse	at	0.998

1st pulse of 1st group of 8	at	$1^s.040$
1st pulse of 2nd group of 8	at	1.120
⋮		⋮
1st pulse of 12th group of 8	at	1.920
Once-per-second pulse	at	1.998
1st pulse of new cycle	at	2.000
⋮		⋮
etc.		etc.

It is therefore possible to measure the signal 100 times per second. The UTC time of emission of the first pulse of the group of 8 from the slave stations may be found by adding the emission delays of Table 5.2 to the times given above.

Table 5.2

U. S. East Coast Loran-C stations and transmission delays*

Designation	Location	Latitude	Longitude	**Emission Delays
M	Cape Fear, N.C.	+34°03.8	-77°54.8	---
W	Jupiter, Fla.	+27°02.0	-80°06.9	13 695 μs
X	Cape Race, Newfoundland	+46°46.5	-53°10.5	29 390 μs
Y	Nantucket, Mass.	+41°15.2	-69°58.7	48 541 μs

*Effective July 1, 1965

** With respect to master station Cape Fear; ms = microseconds.

It should be noted that time signals transmitted by the Loran-C system may be received with specialized receiving equipment only. Pickard and Burns Company, Waltham, Mass., have developed a Loran-C receiver of great precision [Markowitz, 1962a, p. 14].

Thus far only the U. S. East Coast Loran-C chain has been stabilized in time and frequency. It is planned to synchronize internationally cated Loran-C chains with Cape Fear in the future [Markowitz, 1964].

5.33 Agreement in the epoch of U. S. Government time signal broadcasts

Due to the fact that broadcasts from NBS and USNO refer to two different atomic time standards, i.e., NBS-A and A.1, respectively, the epoch of emission of time pulses does not agree exactly. The corrections applied to the clocks at the transmitting stations are reproduced below from USNO, Time Service Announcement, dated September 16, 1964.

In order to bring the two systems into accord, a small adjustment in the epoch of emission of UTC was made at 0^hUT on October 1, 1964.

Table 5.3

Corrections to the epoch of time signal emission from NBS and USNO radio stations

Station Clock	Advance/Retard	Correction in Milliseconds
Master Clock (USNO)	advance	1.6
Loran-C, U. S. East Coast chain	advance	1.6
NBA (VLF and HF)	retard	1.0
NSS (HF)	retard	1.0
NPM (HF)	retard	3.0
NPG	retard	4.0
NPN	no change	
NBS	retard	1.0

The result of these corrections is that the epochs of transmission of time signals from all U. S. Government radio stations may be regarded as identical, for all practical purposes.

5.34 Standard time broadcasts from international stations

Radio stations located about the world which broadcast standard time and frequency are shown in Figure 5.5 and are listed in Tables 5.4 and 5.5.

Stations listed in Table 5.4 are coordinated stations, those listed in Table 5.5 are non-coordinated stations (see Section 5.22). The mode of time signal transmission is given by stating the system according to Section 5.23. The notation A1 means continuous unmodulated wave. Station coordinates are given in general to the nearest minute of arc, except where more accurate information could be found.

The data provided in both tables is based on information given in [BIH, 1965, pp. 8-11], and on corrections published in subsequent issues of the Bulletin Horaire.

It should be understood that broadcast schedules are liable to unpredictable changes and current schedules of transmissions should be consulted when the broadcast of a particular station is required.

5.4 Time Synchronization

The worldwide network of satellite tracking stations obviously requires that time signals transmitted from radio stations in many countries should be coordinated. In other words, not only the scale of time, i.e., frequency, must be based on a common, fundamental standard, but also the epochs of emission of time signals ought to be identical. Achievement of this ideal correspondence is the goal of time synchronization programs of international scope.

Significant advances toward this goal have been made during recent years. Time signal broadcasts from several countries are now synchronized to about ±1 millisecond, mainly through mutual monitoring of time and frequency transmissions. Higher synchronization accuracy may be obtained by use of artificial satellites, portable atomic clocks, and Loran-C. A brief outlay of the methods will follow in Section 5.42. The geodesist

Table 5.5

Time signal broadcast schedules from coordinated stations

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
1	CHU	Ottawa, Canada	-75°45′22″ +45°17 47	3,330; 7,335; 14,670	continuous on all frequencies	pulses spaced 1 sec. apart. 29th, 51st to 59th pulse omitted each min., 1st to 10th pulse omitted after the hour. Pulse 1. 200 msec, prolonged to 500 msec at the min. and 1^s at the hour. Voice announcement.	USNO (7,335 kHz only), BIH
2	DAM	Elmshorn, Germany	+ 9°40′ +53 47	8,638.5; 16,980;	11^h55^m-12^h06^m	ONOGO, followed by English, type A1.	BIH
				6,475.5; 12,763.5	23^h55^m- 0^h06^m (Sept.21-Mar.20)		
				4,265; 8,638.5	23^h55^m- 0^h06^m (Mar.21-Sept.20)		
3	DAN	Norddeich, Germany	+ 7°08′ +53 36	2,614	11^h55^m-12^h06^m 23^h55^m- 0^h06^m		
4	DCF-77	Mainflingen, Germany	+ 9°01′ +50 01	77.5	$1^h,2^h,7^h,10^h$, $19^h,19^h30^m,20^h$, $21^h,23^h,0^h$ no transmission from 19^h on Sat. until 10^h Sun.	type A1 for 10 mins. preceding indicated hours.	BIH

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
5	DIZ	Nauen, Germany	+12°55' +52 39	4,525	continuous		BIH
6	FTA-91	St-André de Corcy, France	+ 4°55' +45 55	91.15	$8^h, 9^h, 13^h, 20^h, 21^h, 23^h$	English, type A1. Sec. pulses 100 msec, prolonged to 400 msec at min.	BIH, USNO (TQG5 only)
7	FTH-42	Pontoise, France	+ 2°07' +49 04	7,428	9^h and 21^h		
8	FTK-77			10,775	8^h and 20^h		(FTK-77 = TQG5)
9	FTN-87			13,873	$9^h, 13^h, 22^h$		
10	GBR	Rugby, Great Britain	- 1°11' +52 22	16	$3^h, 9^h, 15^h, 21^h$	English, type A1.	USNO BIH RGO
11	GIC-27	Rugby, Great Britain	- 1°11' +52 22	7,397.5	9^h and 21^h	one or more of these stations transmit English, type A1 signals simultaneously with GBR and MSF.	BIH RGO
12	GIC-33			13,555			

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
13	GIC-37	Rugby, Great Britain	- 1°11' +52°22	17,685	9^h and 21^h	One or more of these stations transmit English, type A1 signals simultaneously with GIA and MSF.	BIH RGO
14	GPB-30B			10,331.5			
15	HBB	München-buchsee, Switzerland	+ 7°27' +47 01	96.05	8^h15^m	English, type A1.	BIH
16	HBN	Neuchâtel, Switzerland	+ 6°57' +46 58	5,000	5^m-10^m, 15^m-20^m, 25^m-30^m, 35^m-40^m, 45^m-50^m, each hour	1 msec carrier break repeated 5 times at sec., and 250 times at min. First break is exact epoch. Call sign in Morse.	BIH
	HBG	Prangins, Switzerland	+ 6°15' +46 24	75	continuous	100 msec pulses every sec., prolonged for min. mark.	
17	IAM	Rome, Italy	+12°27' +41 52	5,000	from 7^h30^m to 8^h30^m for 10 mins. every 15 mins., daily, except Sun.	Sec. pulses are 5 cycles of 1 kHz modulation, min. marked by 4 pulses spaced 5 msec apart.	BIH

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
18	IBF	Turin, Italy	+ 7°40' +45°03	5,000	from 6^h50^m to 7^h30^m and $10^h 50^m$ to 11^h30^m daily, except Sun.	sec. pulses are 5 cycles of 1 kHz modulation, min. marked by 7 pulses spaced 10 msec apart.	BIH
19	JAS-22	Oyama, Japan	+139°48' + 36 16	16,170	12^h30^m	English, type A1. Emission simultaneous with JJY.	BIH
20	JJY	Tokyo, Japan	+139°31' +35 42	2,500; 5,000; 10,000; 15,000	continuous, except 25^m-34^m each hour	sec. pulses are 8 cycles of 1,600 Hz modulation. Min. mark preceded by 600 Hz tone.	BIH
21	LOL-1	Buenos Aires, Argentina	-58°21' -34 37	5,000; 10,000; 15,000	0^h-1^h, 12^h-13^h, 15^h-16^h, 18^h-19^h, 21^h-22^h	sec. pulses are 5 cycles of 1 kHz modulation. 59th sec. omitted. Voice announcement.	BIH
	LOL-2			8,030	$1^h, 13^h, 21^h$	English, type A1.	USNO (17,183 kHz only)
	LOL-3			17,183			

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
22	MSF	Rugby, Great Britain	- 1°11!5 +52 21.8	60	14^h30^m to 15^h30^m	Sec. pulses are 5 msec of 1 kHz modulation, min. mark is 1000 msec. Call sign and frequency offset announced in slow Morse three times, beginning 0.5 min. before indicated transmission period.	BIH RGO
				2,500 5,000 10,000	0^m-5^m, 10^m-15^m, 20^m-25^m, 30^m-35^m, 40^m-45^m, 50^m-55^m (alternating with HBN) each hour		
23	NBA	Balboa, Canal Zone, USA	-79°34' + 8 57	24 147.85; 5,448.5; 11,080; 17,697.5	5^h, 10^h, 17^h, 23^h	English, type A1.	USNO BIH
24	NPG	Mare Island, USA	-122°16' + 38 06	114.95; 4,010 6,429.51; 9,277.5 12,966; 17,055.2; 22,635	6^h, 12^h, 18^h, 24^h	English.	USNO, (17,055 kHz only) BIH
25	NPM	Lualualei, Hawaii, USA	-158°09' + 21 26	131.05; 4,525; 9,050; 13,655; 17,122.4; 22,593	6^h, 12^h, 18^h, 24^h	English.	BIH

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2 corrections
26	NPN	Guam, USA	+144°43' + 13 27	484; 4,955; 8,150; 13,530; 17,530; 21,760	$6^h, 12^h, 18^h, 24^h$	English.	BIH
27	NSS	Annapolis, USA	-76°27' +38 59	162; 5,870; 9,425; 13,575; 17,050.4; 23,650	$2^h, 6^h, 8^h, 12^h, 14^h, 18^h, 24^h$	English.	USNO BIH
28	OLB-5	Satalice, Czechoslovakia	+14°35' +50 07	3,170			BIH
29	OLD-2			18,985			
30	OMA	Podebrady, Czechoslovakia	+15°08' +50 08	50	continuous, except 10^h to 12^h each day	type A1 signals, call sign in Morse.	BIH
			+14°35' +50 07	2,500	continuous, except 40^m-45^m each hour	pulses are 5 cycles of 1 kHz modulation. Min. mark 100 msec, every 5th min. 500 msec, Call sign in Morse.	BIH

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2-corrections
31	PPE	Rio de Janeiro, Brazil	-43°11' -22 54	8,720;	13^h30^m and 20^h30^m	English, followed by rhythmic.	BIH (not all frequencies all times)
32	PPR			[illegible]; 4,244; 6,421; 8,634; 17,194	1^h30^m, 14^h30^m, 21^h30^m		
33	VHP	Belconnen, Australia	+149°08' -35 15	44	3^h(except Tues. and Wed.) and 8^h	English, certain pulses are omitted.	BIH USNO(8,478 kHz only)
				4,286; 6,428.5; 8,478; 12,907.5; 17,256.8	3^h, 8^h, 14^h, 20^h		
				22,485	3^h, 8^h		
34	VNG	Lyndhurst, Australia	+145°02' - 38 00	5,425	12^h15^m to 22^h	Sec. pulses are 100 msec of 1 kHz modulation. 59th sec. omitted. Voice announcement.	BIH
				7,515	continuous		
				12,005	22^h15^m to 12^h		

Table 5.5 (cont'd)

Number on Fig 5.5	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2-corrections
35	WWV	Greenbelt, Md. USA Note: It is planned to relocate WWV to Ft. Collins, Colorado, by July 1966	-76°50' 52".35 +38 59 33.16	2,500	continuous, except 45^m-49^m each hour (See Fig. 5.4)	See Figure 5.4 and Section 5.211.	USNO, BIH, RGO (15 MHz only).
			-76°50' 52".35 +38 59 30.22	5,000			
			-76°50' 52".35 +38 59 36.1	10,000			
			-76°50' 52".35 +38 59 31.20	15,000			
			-76°50' 50" +38 59 32	20,000			
			-76°50' 51" +38 59 36	25,000			
37	WWVH	Maui, Hawaii USA	-156°28' + 20 46	2,500 5,000 10,000 15,000	continuous, except 15^m-19^m each hour (See Fig. 5.4)	See Fig. 5.4 and Section 5.211.	BIH
38	ZUO	Olifantsfontain, S. Africa	+28°14' -25 58	5,000	continuous		BIH
		Johannesburg, S. Africa	+28°04' -26 11	10,000	continuous		

Table 5.6

Time signal broadcasts schedules from non-coordinated stations

Number on Fig 5.6	Call Sign	Location	Longitude Latitude	Carrier Frequency(kHz)	Operating Schedule (UT)	Time signals	UT2-corrections
a	BVP	Shanghai, China	+121°26' + 31 12	5,430; 9,368	$11^h, 13^h, 15^h, 17^h$ $19^h, 21^h$	English, followed by rhythmic.	BIH
b	FFH	Vaudherland, France	+ 2°29' +48 59	2,500	10^m-20^m, 30^m-40^m, 50^m-60^m during 8^h to $16^h 25^m$ on Tues. and Thurs.	Sec. pulses are 5 cycles of 1 kHz modulation. Min. mark prolonged.	BIH
c	LQB-9	Monte Grande, Argentina	-58°31' +34 45	8,167	23^h 50^m	English.	BIH
d	LQC-28			17,551.5	$10^h 5^m$, $11^h 50^m$, $22^h 5^m$		
e	RBT	Irkutsk, USSR	+104°20' +52 17	5,280; 6,775; 10,900; 13,900	$2^h, 6^h, 12^h, 14^h$ $16^h, 22^h, 24^h$	English, followed by rhythmic.	BIH
f	RES	Moscow, USSR	+37°18' +55 45	100		English, followed by rhythmic.	BIH
g	ROR	Moscow, USSR	+37°18' +55 45	25	$4^h, 8^h, 12^h, 16^h$ [illegible], 24^h	English, followed by rhythmic.	BIH
h	RPT	Tashkent, USSR	+69°10' +41 17	14,650 5,890; 11,580	10^h 18^h	ONOGO during 5 mins. preceding indicated hour, followed by rhythmic.	

Table 5.6 (cont'd)

Number on Fig 5.6	Call Sign	Location	Longitude Latitude	Carrier Frequency (kHz)	Operating Schedule (UT)	Time signals	UT2-corrections
i	RWM	Moscow, USSR	+37°18' +55 45'	5,000; 10,000 15,000; 20,000		English, followed by rhythmic.	BIH
j	WWVB	Ft. Collins, Colo. USA	-105°02' 39".5 +40°40' 28".3	60	continuous, except during certain hours on Tues (See Fig. 5.4)	Special time code (See Section 5.212).	

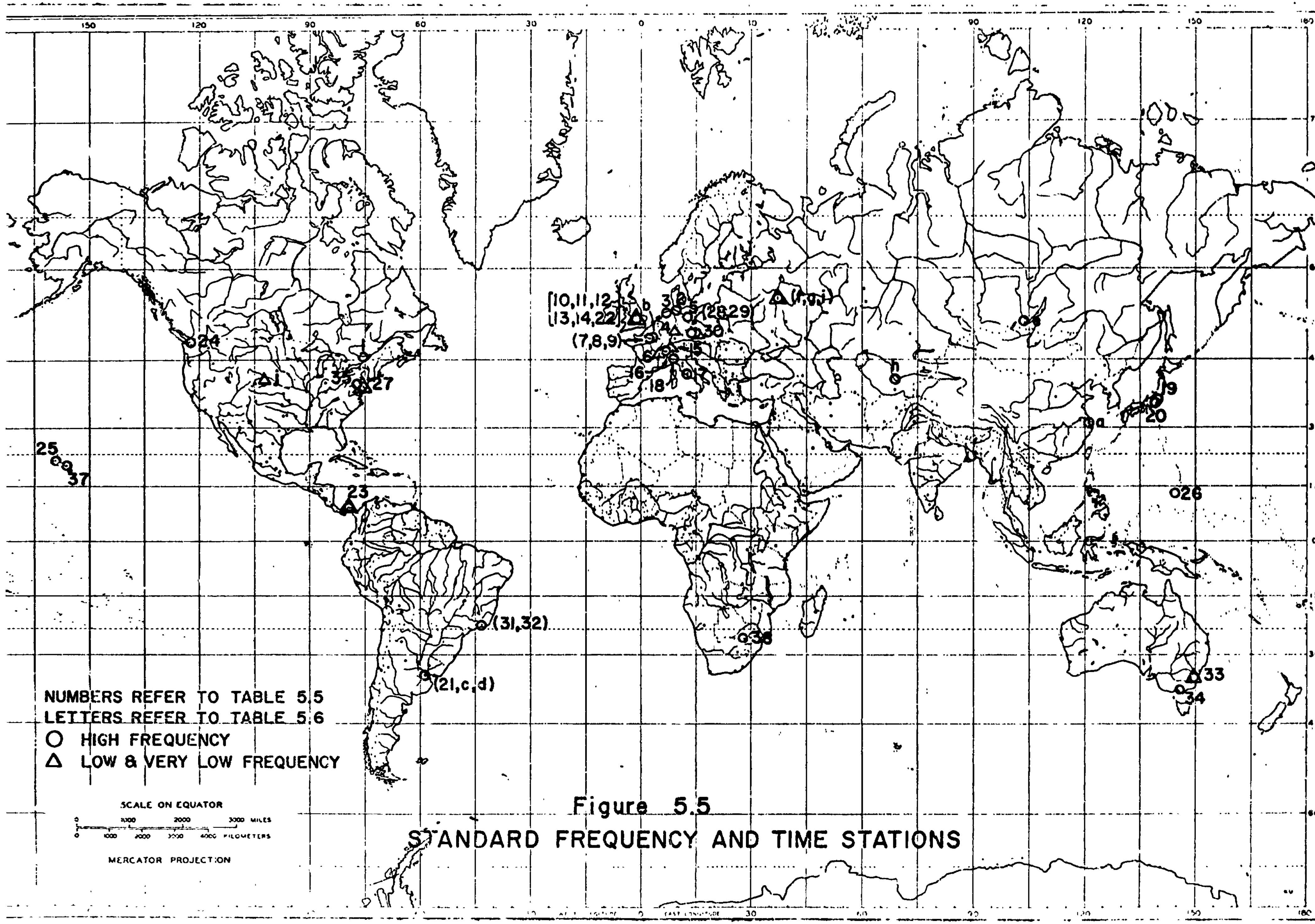


Figure 5.5
STANDARD FREQUENCY AND TIME STATIONS

is usually concerned with either synchronizing his local timekeeper with a radio time source, or comparing his local time standard against a primary time standard. Methods of time comparison are given in Sections 6.2 to 6.4.

No matter how sophisticated the methods employed are, there are practical limitations to the accuracy obtainable, even if one assumes perfect transmitting and receiving gear. Uncertainties due to anomalies in the propagation velocity of radio waves through the atmosphere usually mar the results.

5.41 Propagation characteristics of radio waves

Propagation characteristics of electro-magnetic waves is a study in itself. The International Scientific Radio Union (URSI) maintains a special commission on radio propagation, and the NBS Central Radio Propagation Laboratory almost exclusively studies propagation phenomena.

Due to the complexity of the problem only a brief, general description of the propagation characteristics of different frequency categories can be given here. For details the reader is referred to literature in radio science.

5.411 Propagation characteristics of HF radio signals

High frequency radio signals propagate in a complex manner between the ionosphere and the Earth's surface. Variations in the height of the ionosphere and its profile cause variations in travel time of the HF signals between transmitter and receiver. The principle factors that affect the propagation time of HF signals are: the great circle distance between transmitter and receiver antennas; the number of bounces, i.e., reflections between the ionosphere and the Earth's surface, and the actual height of the reflecting layers of the ionosphere. Several methods to calculate the transmission delay are in use. Two simple methods will be given below.

For distances up to about 160 km a ground-wave propagation path can be assumed. Thus the distance travelled is equal to the length of the great circle, which can be calculated by a variety of methods.

For distances up to 2400 km a one-bounce propagation path can be assumed. During daytime the reflecting layer is assumed to be the E layer, at about 125 km above the Earth's surface. During night time the E layer does not exist.

Long distance HF transmissions are usually reflected by the F2 layer which has an average height of 350 km above the Earth's surface. A one-bounce path may be assumed for distances up to 4000 km.

Considering now that reflections from both E and F2, layers, or even others, may be received, and furthermore, that the number of reflections is uncertain, it is obvious that the calculation of the transmission delay is at best a close approximation. Furthermore, it is possible that the signal was not received via the shortest route but has come around the Earth the longer way.

Once the length of the propagation path, D, is determined, the transmission delay, Δt_{HF}, is usually computed with sufficient accuracy from

$$\Delta t^{S}_{HF} = \frac{D}{V_{HF}} \text{ (D in km)}, \tag{5.5}$$

where V_{HF} = 278,000 km/sec, the usually assumed mean propagation velocity of HF radio waves. Special graphs for the estimation of transmission delays with argument of great circle distances per bounce are in existence. One such graph with explanations is given in [Hewlett-Packard, 1965, p. 4-5].

With proper equipment, synchronization to one millisecond can be obtained with HF at a distance of about 10,000 km, and there are indications that an accuracy of 0.3 milliseconds might be obtained under favorable conditions [Markowitz, 1964a]. To obtain such high accuracies comparisons have to be extended over at least a 24 hour interval and the best available information on propagation conditions has to be utilized.

Best results are usually obtained when the time of comparison is chosen such that the propagation path is either wholly in daylight or in darkness [Nautical Almanac Offices, 1961, p. 444].

The BIH uses an empirical formula to determine the transmission delay for HF waves over distances between 1000 km and 40,000 km [Stoyko, 1964a, p. 2].

The propagation velocity, V_{HF}, is calculated from

$$V_{HF} = (290 - \frac{a}{d+b}) \times 10^3 \text{ km/sec}, \tag{5.6}$$

where $d = \frac{D}{1,000 \text{ km}}$, D in km; a and b are empirical constants,

$$a = 139.41$$

$$b = 2.9$$

The transmission delay is then,

$$\Delta t^S_{HF} = \frac{D}{V_{HF}} \quad (D \text{ in km}). \tag{5.7}$$

In all cases, irrespective of the method by which Δt_{HF} was obtained, the transmission delay has to be subtracted from the clock time obtained from a time comparison.

5.412 Propagation characteristics of LF/VLF radio signals

In general, HF broadcasts are preferred for precise time comparisons and LF/VLF broadcasts for frequency comparisons.

LF/VLF radio waves can be assumed to propagate parallel to the Earth's surface. Irregularities in ionospheric height have much less influence since the ionosphere acts more as a boundary than as a reflector.

Thus, the determination of the transmission delay is much simpler, since all-ground-wave propagation may be assumed for large distances. The delay may be calculated directly from Equation (5.7), substituting the mean propagation velocity for LF/VLF radio waves for V_{HF}; an accepted value for VLF waves seems to be V_{VLF} = 252,000 km/sec [Stoyko, 1964a, p. 2].

Although calculation of transmission delay using VLF is less uncertain, instrumental limitations yield an accuracy in time synchronization somewhat poorer than when using HF signals. The accuracy obtainable is no better than a few milliseconds. Further, different low frequency waves propagate with different phase velocities, thus distorting the arrival time of time pulses. The daily variation in phase of a VLF carrier wave is of the order of 0.04 milliseconds, but it returns to the same value within ± 2 microseconds in a 24^h period. Frequency comparisons extended over such a period yield an accuracy of about 1 part in 10 [Markowitz, 1964a].

5.413 Propagation characteristics of Loran-C

One of the biggest advantages of Loran-C regarding time synchronization lies in its favorable propagation characteristics.

The 100 kHz carrier exhibits ground and sky-wave propagation. The ground wave signal can be positively separated from the sky wave signal by its earlier arrival time by at least 30 microseconds. Daily variations in ground wave propagation have been found to be less than 0.1 msec for distances up to 1200 km [Markowitz, 1964a].

5.42 International time coordination

The epoch of time for satellite tracking must be known to one millisecond, which means that international time broadcasts must be synchronized to at least this or higher accuracy.

Coordination was achieved during recent years so that time pulses from many stations are now emitted in synchronism to about ±1 millisecond, and the same standard frequency is maintained within about ± 1 x 10^{-11} [Markowitz, 1964a].

The time and frequency transmissions of the following countries are coordinated: Argentina, Australia, Canada, Czechoslovakia, France, Great Britain, Italy, Japan, Switzerland, South Africa, and the United States. Although the high accuracy is maintained with using atomic standards it is not necessary that all coordinated stations shall have such standards [Markowitz, 1964a].

The principal methods employed for international time synchronization and recent experiments shall be described below.

5.421 Time synchronization through monitoring

Continuous coordination of time broadcasts from widely separated stations is achieved in principle through monitoring signals emitted from several stations at one receiving station.

For instance, the USNO regularly monitors time broadcasts from stations WWV (all frequencies), NBA (all frequencies), NSS (HF only), NBG (17.055 MHz), VHP (8.478 MHz), CHU (7.335 MHz), GBR (16 kHz), LOL (17.183 MHz), and TQG5 (13.873 MHz), and others. On the other side of the Atlantic ocean, the RGO monitors signals emitted from stations, WWV (15 MHz), NSS (13.575 MHz), GBR (16 kHz), and about twelve others mainly located about Europe. The BIH receives monitoring data from all standard time stations.

The net result of this monitoring system is that corrections can be assigned to the times of emission of the signals with respect to a primary standard, e.g., the USNO master clock. Thus, no matter where time-dependent observations are made (provided they are referred to time signals emitted from one of the coordinated stations) the epoch of observation may be referred to an internationally consistent UT2 system. If the atomic interval is of interest, it may be deduced from frequency comparisons by applying the defined frequency offset.

It should be noted that, although time signals from coordinated stations are emitted in synchronism to about ± 1 millisecond, the epoch of reception governs the accuracy in timing of observations. Propagation anomalies, which may not be rigorously determined, usually prevent full realization of the accuracy inherent in the signal as transmitted.

Particular frequency synchronizations via VLF broadcasts from NBA and GBR have been made between Great Britain and the USA. The methods used and results obtained are given in [Morgan et al., 1965, pp. 905-915]. The A.1 atomic time system, for instance, is based on monitoring of VLF frequency transmissions from the cooperating standard stations (see Section 1.2).

5.422 Time synchronization with portable atomic clocks

Experiments to synchronize master clocks by physically transporting an atomic clock in operation via airline from station to station were begun in 1960. Details and results of the first experiments with an Atomichron are given in [Reder et al. 1961, p. 226]. The conclusions were that clocks anywhere on Earth could be synchronized to ± 5 microseconds or better.

In 1964 and 1965 other experiments followed, which not only correlated time from the USA to Europe and Asia but also provided data on traveling times of HF and VLF radio signals. Results indicate that time might be correlated to about ±1 microsecond by flying clocks [Bodily, 1965].

If in future the need for microsecond synchronization between cooperating stations should arise, it could be established and checked by portable atomic clocks, and maintained through VLF monitoring [Markowitz, 1964a].

5.423 Time synchronization via artificial satellites

In August 1962 the USNO and the NPL conducted an experiment using the active satellite Telstar I to synchronize the USNO master clock and that of the RGO.

In this experiment, time pulses of 5 msec length were transmitted simultaneously over the satellite circuit from the satellite ground stations at Andover, Maine, and Goonhilly Downs, Cornwall. Each station measured the time difference between emitted and received pulse. From these differences the relative setting of the station clocks was determined. It was found that the station clock at Goonhilly was 72.6 ± 0.8 microseconds ahead of the Andover clock.

The satellite ground station clocks were related to the observatory clocks through VLF transmissions from MSF (60 kHz) in Great Britain, and by Loran-C in the United States, respectively.

During the experiment the MSF time signals were monitored at RGO. Thus the Goonhilly clock could be directly related to the master clock at the RGO, and the Andover clock was directly related to the USNO master clock by Loran-C. The results of the comparison showed that on August 27th, 1962, the RGO time standard was ahead of the USNO clock by 2234 ± 20 microseconds.

The all over results established, that time synchronization to ± 1 microsecond is possible between satellite ground stations using active satellites like Telstar. Synchronization to 0.1 microsecond was anticipated with use of more refined equipment. The limiting factors in the Telstar experiment were chiefly the VLF and Loran-C links between the satellite ground stations and observatory clocks, and also the uncertainty in the height of the satellite which was solely based on Minitrack observation.

For further details, especially on equipment used for the experiment, the reader is referred to [Steele et al., 1964].

A more recent experiment of similar nature was conducted jointly by the USNO and the Radio Research Laboratories at Tokyo, Japan, using the NASA satellite Relay II for relatively synchronizing clocks at the satellite ground stations Mojave, California and Kashina, Japan.

In this experiment pulses were transmitted at 100, 1000, and 10,000 pps alternately from both stations. Multiple trace oscilloscopes displayed the transmitted, received, and calibration pulses, which were photographed automatically at certain intervals.

Preliminary results indicated that communications satellites such as Relay II may be used to synchronize clocks at tracking station to 0.1 microseconds [Frequency, May-June 1965, p. 13]. A preliminary report of the experiment by Wm. Markowitz and C. A. Lidback, is supposed to be published in "Proceedings of the 19th Annual Symposium on Frequency Control, 1965".

VI. GEODETIC USE OF DISTRIBUTED PRECISE TIME

6.1 Introduction

In the foregoing chapter we established that precise time signals are disseminated worldwide. The question now is, how does or should the geodesist make use of this precise radio time with a minimum of loss in the precision inherent in the time signal as transmitted. This may be one criterion for selecting a specific method of time comparison. On the other hand, we have to consider the timing accuracy required in different geodetic operations.

Considering the latter aspect, we may conveniently divide the discussion on methods of time comparisons in three groups: those that yield highest accuracy, applicable to artificial satellite observations; those of medium accuracy, applicable to first order astronomic longitude determination; and finally those of low accuracy, applicable to determination of approximate longitudes. The latter group will be considered very briefly only.

Obviously, different accuracy requirements call for a variety in equipment and methods of time comparison. To consider all methods and the instrumentation involved is beyond the scope of this paper. Therefore, outlines of some methods in use will be given only, in descending order of the accuracy obtainable.

Finally, in Section 6.5 the use of two major Time Service Bulletins will be explained, so that epochs of observations may be reduced to universal time (UT1 or UT2), or to atomic time, as the requirement may be.

It should be emphasized that any method of comparison, i.e., calibration of a local time generator against a standard radio time source must eventually yield two quantities: a correction to the epoch of the locally generated time, and the drift rate of the local timekeeper.

6.2 Time Comparison Methods of Highest Accuracy

The methods outlined below yield an accuracy in timing of observations of the order of one millisecond or better. Such accuracies are required, for instance, in observations of artificial satellites for geodetic purposes, where an error of one millisecond in timing alone contributes about 8 meters in the uncertainty of the observer's position [Markowitz, 1963, p. 217].

A high precision, stable quartz crystal chronometer, or a combination of quartz crystal oscillator, frequency divider and clock, is essential for millisecond timing. Usually time signal broadcasts from stations such as WWV are used as time reference when high accuracy is required.

6.21 Time comparisons using HF transmissions

The general characteristics of HF radio wave propagation have been discussed in Section 5.411. For best results, the time comparisons should be scheduled for an all-daylight or all-night propagation path between broadcasting station and receiver.

6.211 Tick phasing adjustment method

The equipment needed consists basically of a stable local time generator, hereinafter called station clock, a good quality short wave radio receiver, and an oscilloscope.

Naturally, the available instrumentation will dictate the exact comparison procedure to be followed, hence general requirements can be delineated only.

The station clock must incorporate a tick phasing control. That is to say, it must be possible to manually shift the phase of the seconds pulses generated by the station clock. The tick phasing control must permit continuous phase shifts, or shifts in small increments.

The quality of the receiver (hence cost) will depend on accuracy requirements and the expected strength of the radio signals at the receiving station. The antenna should be preferably of the directional type.

Oscilloscopes may be of the multiple trace or single trace type. They must, however, permit adjustment of sweep speed from about 0.2 sec/cm down to about 1 msec/cm, this is to say, that at a sweep speed of 1 msec/cm one centimeter interval on the oscilloscope scale is swept by the signal pulse in one millisecond. The sweep speed should be stable.

To illustrate the tick phasing adjustment method let us take the case of calibrating a station clock against time signals emitted from a standard time station such as WWV.

The station clock generates seconds pulses which cause triggering of the sweep of a single trace oscilloscope. Seconds pulses from WWV are also fed to the oscilloscope, where they are displayed at the instant when the oscilloscope sweep is triggered. The leading edge of the WWV 5 msec (5 cycle) pulse is the time reference.

Initially, the station clock pulse and the received pulse may be apart by as much as a half second. By changing the sweep speed of the oscilloscope, the leading edge of the 5 msec pulse of WWV may be located with respect to the station clock pulse. By means of the phasing control, and successive oscilloscope sweep speed adjustments, the two pulses are brought into near coincidence.(Phase shifting does not change the frequency of the oscillator.)

Once near coincidence is established, the difference between the station clock pulse and the leading edge of the displayed WWV pulse is recorded, in milliseconds and fractions thereof. This difference is the correction to the initial setting of the station clock. The correction is either read visually off the oscilloscope scale, or it may be recorded photographically.

It should be noted that the oscilloscope reading establishes the millisecond difference between the station clock tick and the received tick only. The total correction to the station clock may comprise hours, minutes and seconds. Usually, hours, minutes, and seconds counters (or the hands of a clock face) are pre-set to a desired value and manually released at an appropriate instant, e.g., just before a minute tick (double tick with WWV) is received. The millisecond setting of the station clock is usually displayed by decade counters synchronized with the phasing control which can be read to 0.1 msec or better.

Repetitions of the comparison at certain intervals will exhibit a change with time in the difference between the pulses, from which data the drift rate of the station clock can be accurately determined.

As mentioned before, this comparison method may be used with a variety of instruments. In the case of continuous phasing control, for instance, the pulses from station clock and radio signal are brought initially into full coincidence. The station clock then beats seconds in synchronism with the received seconds pulses. Successive checks on the

the synchronism of emission will show progressive deviations of the station clock pulses from the received pulses from which the rate of the station clock may be determined.

Several modifications and improvements of the principle discribed above are possible. Thus it may be desirable to use an average of several received pulses in order to account for propagation anomalies. In that case, a time exposure of several seconds may be made, provided the sweep speed of the oscilloscope remains constant. The photographic oscillogram will show several pulses which permits estimation of a mean arrival time of the WWV tick, and a mean correction may be determined.

Time comparators can also be used in connection with this method. If hooked up to the oscilloscope, the time comparator will show, on decade counters, the exact time difference between the time of sweep triggering and the leading edge (left end) of the received pulse. The comparator may also produce modulated time markers on the oscilloscope at small intervals which facilitate comparison reading to about 10 microseconds.

It has been shown that tick phasing comparisons yield millisecond accuracy or better. No matter what basic and auxiliary instrumentation is employed, as long as all components fit the specifications, excellent results will be obtained. For specific details on instrumentation the reader is referred to manufacturer's literature, and for details on oscilloscopes to textbooks in electronics. See also [Hewlett-Packard, 1965, pp. 2-2 to 2-7] and [Puckle, 1951].

6.211 Time comparison with stroboscopic devices

Contrary to oscilloscopes which display the wave form of an impulse, stroboscopes exhibit flashes at the instant of triggering caused by an impulse. Mechanical and electronic stroboscopes are used for time comparisons.

The following discription is taken from [Bundesamt fur Eich-und Vermessungswesen].

The main parts of the mechanical stroboscope are a cathode ray tube and a synchronous motor driven by a 50 Hz output of the station clock oscillator. The motor drives a disc of about 20 cm diameter. The disc carries a scale divided into 100 units which rotates once per second; one division, rotating past a fixed index marker, corresponds to about 0.01 second.

During the time comparison the received radio pulse causes triggering of the flash underneath the index marker and the disc is adjusted such that the zero mark coincides with the index marker at the instant of flashing. Now the seconds pulse from the station clock is fed to the stroboscope causing again triggering of the flash. At this instant the scale reading is logged. If the rotation speed of the disc is properly calibrated, the reading gives the direct difference between station clock and received pulse to 10 milliseconds.

For higher comparison accuracy a combination of oscillograph (polar) and electronic stroboscope is used. Instead of the rotating disc a circle, produced by a 50 Hz frequency input, appears on the oscilloscope. One rotation of the circle takes about 0.02 seconds. Superimposed on the circle is an adjustable, graduated scale. The seconds pulses from the station clock or radio signal cause to trigger the stroboscope flashes which appear in the circle. With the adjustable scale, differences between the flashes can be read to 0.5 milliseconds.

The mechanical and electronic stroboscope can be used together, one supplementing the other. Repeated comparisons will yield the drift rate of the station clock.

A more modern stroboscope consists of four cathode ray tubes with horizontal and vertical electrostatic deflection plates. The horizontal sweep of each of the cathode ray tubes is derived from a linear time base which is triggered by the station clock pulse. Superimposed on each tube is a time scale. The first tube has a time scale the unit of which is 0.1 second, the fourth tube's unit is 0.1 millisecond.

The received seconds pulse is fed to the tubes via the vertical deflection plates and is thus superimposed on the scales. This permits reading of the difference between the time of horizontal sweep triggering (derived from the station clock) and the time of reception of the pulse from the radio source, to 0.1 millisecond.

Again, several modifications such as photographic registration, and auxiliary counters could become part of such a comparison system.

6.213 Time comparison using delay counters

Time comparisons of high accuracy may also be made using time comparators independent of oscilloscopes.

In this case the delay between station clock pulse and radio signal pulse is counted, in milliseconds or better, by a decade counter.

In principle the decade counter is started by the station clock pulse and stopped by the received pulse. A drawback is that the station clock starts the counter on-time but the cut-off by the received signal may be less precise due to fading and jitter of the received signal. Nevertheless, millisecond accuracy may be obtained under favorable reception conditions [Szádeczky-Kardoss, 1964, pp. 181-190].

Displaying the small residual delays on an oscilloscope improves the results tenfold.

6.22 Time comparisons using VLF transmissions

The aforementioned high precision comparison methods usually utilize HF transmissions of the WWV type, i.e., continuous time signal transmission. Readings are made against the leading edge of the received pulse which is usually well defined and constitutes the time reference.

VLF techniques are usually preferred for frequency comparisons, i.e., time interval comparisons. Owing to the inherent slow rise time of seconds pulses the correction to the initial setting of the station clock is difficult to determine using VLF transmissions.

The equipment needed for VLF comparisons consists basically of a station clock with oscillator output, a VLF receiver, a VLF phase comparator, and possibly an oscilloscope. The set up is more complicated than that for HF comparisons due to more stringent receiver antenna requirements. The principle of a VLF comparison is as follows [Hewlett-Packard, 1965, pp.2-7 to 2-16].

Once the initial setting of the station clock is determined, the local oscillator frequency is compared with a VLF standard frequency via a phase comparator. The comparison is either made continuously or over an interval of several hours. The long comparison period is required due to diurnal phase variations. (See Section 5.412)

For phase comparisons several specialized devices are available. In principle they are either of the decade counter or self-recording type. The latter produce a plotted record of the phase differences, the former are electronic counters that record elapsed time intervals. The decade counter type is similar to the one described in Section 6.23 with the difference that the interval count is started and stopped by the frequency output of the station clock (say 1000 Hz) and the received frequency, e.g., 20,000 Hz from WWVL.

In any case, it is possible to calculate the drift rate of the local oscillator from the time interval counts or the recorded phase differences. The fractional frequency difference between the local standard and the received frequency is equivalent to the rate of change in phase difference measured over a certain time interval. The relationship between the fractional frequency difference and the time error of the station clock during a measured interval is

$$\Delta t = - \frac{\Delta f}{F} T, \tag{6.1}$$

where Δt = station clock error; Δf = frequency error; F = nominal frequency of the oscillator; and T = comparison interval.

For detailed descriptions of VLF comparison methods the reader is referred to literature on radio communication systems. See also [Hewlett-Packard, 1965, pp. 2-7 to 3-7].

6.23 Specific methods of time synchronization

6.231 Time comparison method used at USC & GS satellite observing stations.

The USC & GS uses a specific method for calibrating clocks at satellite observing stations. The method is of interest because it shows the possible separation of the two aspects of clock calibration: initial setting of the clock, i.e., establishment of the epoch, and control of the rate of the station clock. The following description is taken from [USC & GS, 1965, pp. 6-7].

Each satellite station is equipped with a station clock, a VLF receiver, and a VLF phase comparator. The station clocks consist of a time code generator that derives a 100 kHz frequency from a crystal oscillator having a stability of better than $\pm 3 \times 10^{-10}$, and a frequency drift rate of less than $\pm 3 \times 10^{-10}$ per day.

The time code generators are initially set by means of a very precise, portable quartz crystal chronometer. The oscillator of this travelling chronometer has a frequency stability of better than $\pm 1 \times 10^{-10}$, and a frequency drift rate of less than 1×10^{-10}.

The travelling chronometer is synchronized to the master clock at WWV before commencement of a station clock setting trip, and it is checked after a trip. Experience has shown that the uncertainty in the travelling chronometer is less than ± 10 microseconds after a five day field trip. Hence, it may be assumed that the station clocks can be set to within 10 microseconds of the WWV clock.

It should be noted that the station clocks are set with respect to the pre-transmitted signals of WWV. Through this procedure the uncertainties in clock setting due to propagation anomalies are circumvented.

Once the station clock is set, VLF carrier frequencies are used to control day-to-day variations in the time kept by the station clock. Two VLF phase comparators constantly compare the station oscillator's frequency against two VLF transmissions. From these records time corrections are determined. The time code generator is reset when the accumulated uncertainties in the time correction approach ± 40 microseconds.

Thus, the synchronization of the station clocks with respect to the pre-transmitted WWV signal is always within ± 50 microseconds.

6.232 A unique system of time synchronization

The Chronofax-103 (Figure 6.1) manufactured by Newtek, Inc., represents to this writer's knowledge a unique system in the sense that it operates in synchronism with a received HF radio time signal.

Although it appears that extensive field tests are still lacking, a short description, based on manufacturer's literature shall be given. This author has witnessed a demonstration of the Chronofax in September 1965.

The Chronofax is a compact field chronometer that can operate 24 hours from internal batteries, independent of radio reception. Here, the synchronization shall be described only.

The Chronofax is usually set by synchronizing the once per second pulse derived from an internal 3 MHz oscillator, which reaches a stability of 1×10^{-8} within 15 minutes after the clock is turned on, to a received radio signal. Setting is accomplished with the aid of a special time correlator unit, whose main features are a cathode ray tube, sweep speed adjustment, and continuous phasing control.

A 1 kHz output from the Chronofax causes triggering of the cathode ray tube sweep. The seconds pulses from the standard time station, received via a good HF receiver are displayed on the tube as short flashes at the instant of triggering. By successive adjustments of the sweep speed and phasing control the flashes originating from the radio signal are brought into coincidence with the left hand grid line of the cathode ray tube.

Once this is accomplished, an arm button is depressed during the next interval between two seconds pulses. The leading edge of the radio signal pulse sets the clock which from now on beats seconds in synchronism with the radio signals to 0.5 milliseconds. Hours and minutes are preset manually on the Chronofax panel. To have near perfect correspondence between Chronofax time and radio time the clock is started with the minute tick of the radio signals.

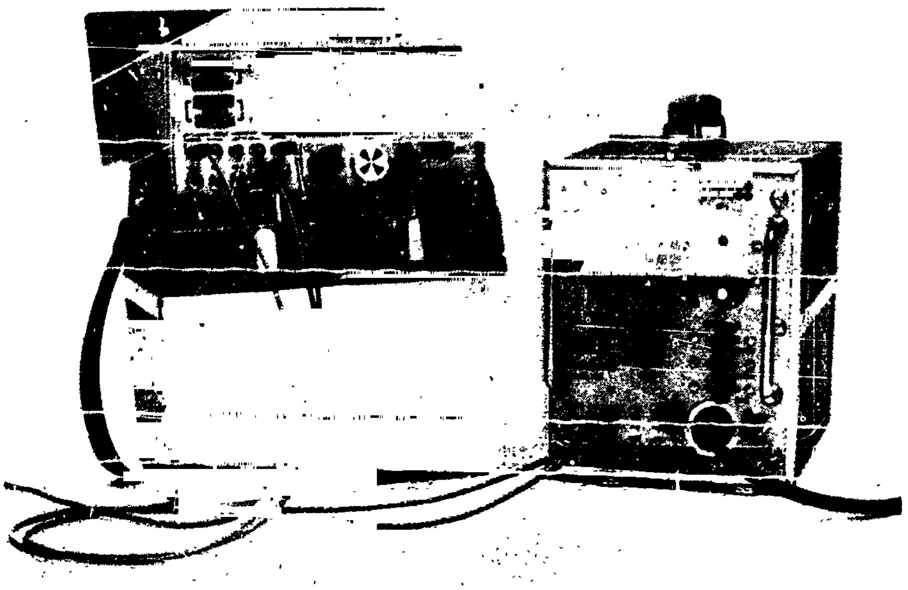


Figure 6.1: Newtek Chronofax with time correlator,

Under exceptionally good receiving conditions the Chronofax supposedly can be set accurately without the time correlator.

Once the clock is set it keeps step with the radio signals with a drift of less than one millisecond per 24 hours.

The time of any event is printed on voltage sensitive paper to milliseconds. The printed time record is in BCD code (see Figure 5.3b). A sample is shown in Figure 6.2 below.

The drift rate of the Chronofax can be determined at arbitrary intervals simply by connecting it and the HF receiver to the time correlator and reading the difference between clock pulse and received pulse on the cathode ray tube.

Hours						Minutes							Seconds							$0^s.1$				$0^s.01$				$0^s.001$			
Tens		Units				Tens			Units				Tens			Units				Units				Units				Units			
2	1	8	4	2	1	4	2	1	8	4	2	1	4	2	1	8	4	2	1	8	4	2	1	8	4	2	1	8	4	2	1
	•			•	•		•	•			•	•		•			•	•	•		•	•	•	•					•		•

Figure 6.2: Section of Chronofax time record. The time is recorded by placing a mark in a column or leaving it blank. Time shown is $13^h\ 33^m\ 27^s.785$.

6.3 Time Comparison Methods of Medium Accuracy

The methods outlined in this section usually yield a comparison accuracy of about 0.01 second, which is generally considered adequate for first order astronomic longitude determination.

Almost invariably the necessary instrumentation consists of a chronometer, either mean or sidereal preferably of the quartz crystal type, a HF receiver, a chronograph, and an amplifier. Actually, all methods in this group may be called chronograph comparisons. They are at present the most widely used methods for the determination of the correction to, and the rate of, a field chronometer.

Chronographs are devices that produce a graphical record of the beats of a chronometer or a radio signal. They are usually of two types: drum or tape. The latter are more easily portable and usually preferred. Both types may have one or two pens. The chronographs may be driven by electric current, clockwork, or weights, at one or more constant speeds; a convenient speed for time comparisons is 1 cm/sec.

The time signals used as reference ought to be of the once per second pulses type, such as emitted by WWV. Rhythmic signals or ONOGO (see Section 5.2?) are not suitable.

Usually, the chronometers have electric break circuits by which the pen circuit of the chronograph can be broken for about 0.2 seconds at each second. Mechanical chronometers may break each second or every second second only, depending on the type used.

The small current which can be passed by the clock often needs amplification to work the chronograph pen. The necessary amplifiers may contain magnetic or electronic relays, the latter being preferable. An audio filter, which is part of the amplifier, filters out noise and the audio frequencies while the seconds pulses may be recorded without interference.

It follows that during the time comparison the chronometer ticks and the radio pulses are fed to the chronograph via the amplifier. In the case of a two pen chronograph each signal may actuate one pen; with a single pen chronograph both signals actuate the same pen. In the former case a pen equation should be determined by switching both pens to the chronometer output. Similar reasoning applies to the case when two amplifiers are used, or when the radio signal is amplified only. For higher accuracy the relay delay of the amplifier has to be determined also; usually it is assumed to be constant within 0.01 second.

The graphical record of the comparison will show a continuous record of the received seconds pulses and the chronometer ticks in the form of a broken line. The leading edges of the breaks are taken as the instant of the seconds breaks.

Scaling the chronograph record by means of a transparent scaling fan establishes the chronometer correction. The scaling fan permits the determination of the chronometer time of the radio signal to 0.1 second and 0.01 second can be estimated. One comparison is extended over a certain interval, usually 21 unambiguous radio breaks, and a mean chronometer and mean radio time for the interval is calculated. Hours, minutes and even seconds must be identified on the chronograph record for both chronometer and radio time.

Depending on whether a mean or a sidereal chronometer is used, the correction to the chronometer time is found directly from the comparison, or through further computations.

Repetition of the comparison will establish another chronometer correction. From the difference between the corrections and the known time interval between comparisons the rate of the chronometer can be easily calculated.

In first order longitude work it has become customary to make hourly time comparison. If the rate of the chronometer is nearly constant, as it is the case with crystal chronometers, this stipulation is obviously too narrow.

For further details and actual examples the reader is referred to [Hoskinson and Duerksen, 1947, pp. 5-14] and [Thorson, 1965, pp. 5-14].

6.4 Time Comparison Methods of Low Accuracy

This group of comparison methods comprises aural and aural-visual methods, and the so called extinction method. These methods are used mainly in connection with rhythmic signals (see Section 5.23).

In the aural comparison the operator listens to the radio and chronometer ticks by means of ear phones and records the chronometer times of coincident ticks (remember that in the rhythmic signals there are 61 ticks per mean minute and a prolonged dash at the minutes).

In the aural-visual method one listens to the radio ticks and observes the chronometer seconds hand, noting the chronometer time of the dashes.

In the extinction method the chronometer is wired to the radio such that the radio is silenced when coincident seconds occur. These coincidences are noted.

Rather elaborate techniques have been worked out in the past to obtain reliable results of a reputed accuracy of about 0.01 second. This author considers all of these methods as obsolete however. The interested reader is referred to [Briddle, 1958], Chapter XIII, and to [Bomford, 1962, pp. 305-307].

6.5 Corrections to Radio Time Signals

Let us assume that an accurate time comparison has been made, and further, that the time signal from a coordinated station was used as the time reference, the time reference was UTC as received.

Small corrections have to be applied to reduce the epoch of an observation to a desired time system: UT1, UT2 or AT, as the case may be. Corrections will depend on the accuracy strived for.

In the following discussion of the corrections we aim at millisecond accuracy. The magnitude of the corrections will indicate those that may be neglected if a less stringent requirement is preferable.

Firstly, a correction needs to be applied to the chronometer time for the propagation delay of the time signal between transmitting and receiving antennas (see Section 5.41). The correction is always subtracted from the epoch of an observation and may be calculat d from Equations (5.5) or (5.7), depending on the transmission frequency.

The transmission delay, if applied correctly, relates the epoch of an observation to UTC as transmitted from the reference station.

It is of course possible to allow for the propagation delay at the time of comparison, e.g., through phase shifting. In this case the recorded chronometer time refers directly to UTC as transmitted.

Further corrections have to be applied for the deviation of UTC, as emitted, from the desired time system to which the observations should be referred, invariably these systems are either UT1, UT2, AT, or occasionally UTO.

The final time of emission of the signal in any one of these systems may be deduced from information contained in so-called Time Service Bulletins.

Each time service usually publishes corrections to standard time and frequency broadcasts transmitted from its own stations, and from closely associated stations. Two such correction bulletins will be discussed in detail: that of the USNO and the Bulletin Horaire of the BIH.

6.51 Explanation and use of the U.S. Naval Observatory time correction publications

The USNO periodically publishes several papers concerning time signal transmissions.

These are:

(1) Time Service Announcements: usually containing advance information on frequency offsets and changes; changes in broadcast schedules; announcements of step adjustments in phase; etc. The information concerns usually U.S. Naval radio stations, Loran-C stations, and closely co-ordinated stations.

(2) Time Service Notices: usually containing definitions and changes in definitions; policies followed; etc. The information is usually of more fundamental nature, concerning the Time Service in general.

(3) Preliminary Emission Times: providing preliminary corrections to UTC emission times. This notice is published weekly.

(4) Time Signals Bulletins: containing final corrections to UTC emission times for a number of stations, and ob-

servational results from the USNO and its sub-station Richmond. The Bulletin is usually published quarterly for periods about one year in arrears.

Items (1), (2), and (4) are mailed to regular subscribers to the Time Service. Item (3) is sent upon specific request for a stipulated period. The manner in which publications (3) and (4) are used will be explained below.

Preliminary Emission Times and the Time Signals Bulletin, hereafter called PET and Bulletin, respectively, may be used to reduce the epoch of an observation, recorded with respect to UTC, to UT0, UT1, UT2, or A.1 as the case may be.

Specimens of PET and Bulletin are shown in Figures 6.3 and 6.4, respectively. A specific example of the reduction of an epoch will be given later on. The difference in the corrections listed in the two publications is of the order of about ±10 milliseconds.

PET is published weekly, the Bulletin is usually published quarterly. The latter gives final times of emission in terms of UT2 and A.1, about 12 months in arrears, for closely cooperating stations. This publication should be used for precise time reductions.

The exact number of stations for which final emission times are provided varies. During the past three years the following stations have been included consistently: NBA, WWV, CHU, GBR, LOL, NSS, NPG, and TQG5. Other stations which have been included intermittently are WWVH and VHP. The corrections to the epoch of emission of UTC are given in the sense UT2-UTC.

It should be noted that the notation "signal" and "UT2C" used in PET and the Bulletin, respectively, corresponds to our notation UTC. It designates the emission time of standard time signals from any one of the cooperating stations.

UT2 is the uniform universal time adopted by the USNO. It is obtained from PZT observations at Washington, D.C. and Richmond, Fla., which are referred to the atomic time A.1. The observations are smoothed over about two months, assigning a weight of 1 for Washington and 2 for Richmond [USNO, 1962a]. The observations are corrected for observed polar motion and extrapolated seasonal variation (see Chapter IV).

The final times of emission are final in the sense that no further corrections are published. This does not imply that the epoch of an observation has been reduced to a uniform time system once the corrections UT2-UTC are applied.

One should be aware of the fact that UT2, obtained from the Bulletin, is based on the conventional longitude of washington of $-5^h08^m15^s.729$. Thus, remembering what has been said about conventional longitudes in Section 2.23, precisely reduced astronomic longitudes should identify the source from which time corrections have been extracted.

Let us assume that the mean epoch of an observation was recorded with respect to a chronometer, corrected and rated against UTC transmissions from a particular station. The reduction to a final time system consists then of two parts (provided the propagation delay between the receiving and transmitting sites has been accounted for): a correction of the form $\Delta i = T^i$ - UTC, where i and T^i stand for UT2, UT1, UT0, or A.1, as the case may be; and a correction for the variation of the meridian due to polar motion (see Section 4.2).

From PET Δi is obtained directly. From the Bulletin only ΔUT2 and ΔA.1 can be obtained directly by interpolation in the appropriate columns of parts I and IV (Figure 6.4). ΔUT1 and ΔUT0 are found through the relationships

$$UT1 = UT2 - S \tag{6.1}$$

and

$$UT0 = UT2 - V \tag{6.2}$$

where V = P + S; S being the seasonal variation correction, ΔS, which is considered constant, and P is the effect of polar motion on longitude, $\Delta\lambda$, (hence time), peculiar to each station. The quantities S and V are tabulated in part I of the Bulletin.

The tabulated quantities T^i - UTC are to be used in the following sense.

UTC epoch	tabulated quantity	epoch of adopted UT2
$3^h\ 00^m\ 00^s.0000$	0175	$3^h\ 00^m\ 00^s.0175$
$3^h\ 00^m\ 00^s.0000$	8976	$2^h\ 59^m\ 59^s.8976$

In general $\Delta i = T^i - UTC$, if the tabulated quantity is smaller than 500 milliseconds, and if T^i = A.1;

$\Delta i = (T^i - UTC) - 1$, if the tabulated quantity is greater than 500 milliseconds.

U. S. Naval Observatory
Washington, D. C. 20390

No. 178 — 19 August 1964

PRELIMINARY EMISSION TIMES for Signals from NBA, GBR, WWV, CHU, and Other Coordinated Stations

For 19 August 1964

UT1 - Signal, 895.

UT2 - Signal, 880.

A.1 - Signal, $3^{s}.202$.

UT0 - Signal, 881.

UT1 is the reading of a clock which indicates time UT1. Similarly for UT2 and A.1. Signal is the reading of the transmitting clock. The quantities tabulated are therefore the amounts, in milliseconds, by which signals are emitted late with respect to clocks which indicate UT1, UT2, and A.1, respectively.

Provisional Coordinates of the Pole

For 19 August 1964

	x	y
B. I. H.,	+ 0.251	+ 0.000
Pole of 1900-05,	+ 0.282	+ 0.159

Corrections of +0.031 and +0.159 were added to the provisional B. I. H. values to obtain those referred to the pole of 1900-05.

Figure 6.3: Preliminary Emission Times specimen.

U.S. NAVAL OBSERVATORY

WASHINGTON 25, D. C.

TIME SIGNALS

BULLETIN 207 — 20 MAY 1965

I. FINAL TIMES OF EMISSION, UT2 - UT2C.

1. The times of emission are on the system UT2, obtained by correcting the observations for observed variation in longitude and for provisional seasonal variation. They are based on a conventional longitude of Washington, D.C., of $5^h 8^m 15\overset{s}{.}729$ west of Greenwich. See Time Service Notices Nos. 9 and 10.

2. The quantities listed are given in the sense of UT2 - UT2C. Thus, on 3 July 1964, a clock indicating the adopted UT2 of the Naval Observatory was 0.0995 seconds behind a clock synchronized with the emitted signal from NBA.

3. Corrections for intermediate dates may be obtained by interpolation, except as noted.

4. The times of emission are obtained by smoothing the times of reception for several days near each date and correcting for time of transmission, K.

5. UT2C is the reading of the transmitting clock.

UT2 - UT2C

	Signal:	NBA	WWV	CHU	GBR	LOL	NSS	NPG	TQG5
		All Freq.	All Freq.	7335kc	16kc	17183kc	H.F.(2)*	17055kc	13873kc
	K	(1)*	0001	0026	0199	0299	0002	0139	0220
	UT	13h	3h	13h	15h	21h	2h	18h	13h
1964	Jul 3	9005	8987	8980	9000		898	893	895
	13	8970	8952	8940	8965	8875	895	892	895
	23	8924	8906	8897	8920		890	887	889
	Aug 2	8861	8842	8842	8859		884	881	883
	12	8790	8772	8782	8790	8750	877	873	876
	22 (3)*	8724	8706	8705	8720	8680	870	866	870
	Sep 1	9659	9642	9638	9624	9612	964	960	962
	11	9585	9567	9565	9545	9545	956	935	954
	21 (4)*	9495	9477	9480	9463	9464	948	942	945
	Oct 1	9416	9399	9400	9388	9365	940	936	937

6. The seasonal variation, S, is the same for Washington and Richmond, but the polar variation, P, is different. To convert UT2 to UT1 and UT0 use the Formulas:

$$UT1 = UT2 - S,$$
$$UT0 = UT2 - V,$$

where V = S + P.

1964	S	V(W)	V(R)
Jul 3	+.018	+.025	+.023
13	+.012	+.020	+.017
23	+.005	+.015	+.011
Aug 2	-.003	+.009	+.004
12	-.010	+.003	-.002
22	-.016	-.003	-.008
Sep 1	-.022	-.008	-.013
11	-.026	-.012	-.017
21	-.028	-.014	-.020
Oct 1	-.029	-.016	-.022

*(Explanatory notes are given in section 7.)

Figure 6.4: Time Signals Bulletin Specimen.

7. NOTES.

(1) K = 0114 on 18 kc/s and 0118 on high frequencies.

(2) High Frequencies 5870, 9425, 13575, 17050, and 23650 kc/s. For 122 kc add 0015, for 162 kc add 0005.

(3) Transmitting clocks of all coordinated stations except GBR retarded 0.1000 sec. at 0^h of 1 September 1964. GBR retarded 0.0955 sec.

(4) Transmitting clocks retarded at 0^h of 1 October 1964 as follows:
NBA, NSS, WWV retarded 0.0010 sec; NPG retarded 0.0040 sec; NPM retarded 0.0030 sec.

II. ADOPTED UT2 - A.1.

8. The following are the adopted differences, UT2 - A.1, for every tenth day, which were used to derive the final times of emission. A.1 is a system of atomic time based on cesium resonators of the Naval Observatory and other laboratories. The values are based on observations made with the PZT's of Washington and Richmond, Florida, and are smoothed over an interval of about two months. The quantity, UT2 - A.1, is the difference between a clock which indicates UT2 and one which indicates A.1.

UT2 - A.1

1964	Jul	3.0	$-3^s.2403$	1964	Aug	2.0	$-3^s.2936$	1964	Sep	1.0	$-3^s.3524$
		13.0	-3.2567			12.0	-3.3135			11.0	-3.3728
		23.0	-3.2743			22.0	-3.3330			21.0	-3.3948
									Oct	1.0	-3.4166

III. OBSERVATIONS.

9. The quantities marked O-A give the difference, UT2 (Observed) - UT2 (Adopted). The fraction of the Besselian year is given by τ.

Date 1964	Julian Date 2438000+	τ 1964	WASHINGTON Stars	WASHINGTON O-A	RICHMOND Stars	RICHMOND O-A
Jul 1.3	577.8	-.5017	9	-.003	--	---
2		-.4989	--	---	16	+.002
3	579.8	-.4962	--	---	16	+.015
4		-.4935	--	---	13	-.004
5		-.4907	--	---	19	-.014
6		-.4880	--	---	--	---
7		-.4852	--	---	--	---
8	584.8	-.4825	5	+.007	19	-.011
9		-.4798	15	-.008	20	-.017
10		-.4770	11	.000	14	+.019
11		-.4743	11	-.005	18	+.001
12		-.4715	8	+.001	20	+.008
13	589.8	-.4688	--	---	17	-.004
14		-.4661	--	---	25	+.001
15		-.4633	--	---	6	-.005
16		-.4606	7	-.023	11	+.017
17		-.4579	16	-.010	--	---
18	594.8	-.4551	28	-.001	19	.000
19		-.4524	20	+.003	12	+.018
20		-.4496	26	+.002	16	+.008
21		-.4469	--	---	8	+.002
22		-.4442	7	.000	15	+.013
23	599.8	-.4414	16	+.006	16	-.007
24		-.4387	14	+.005	15	-.007
25		-.4360	--	---	6	+.016
26		-.4332	--	---	19	+.006
27		-.4305	28	+.005	20	-.001
28	604.8	-.4277	15	+.007	16	+.007
29		-.4250	10	-.003	8	+.006
30		-.4223	--	---	14	-.005
31		-.4195	19	+.006	19	+.009
Aug 1	608.8	-.4168	19	.000	11	-.006
2	609.8	-.4141	--	---	20	.000
3		-.4113	--	---	14	-.005
4		-.4086	--	---	16	-.005
5		-.4058	--	---	20	+.003
6.3		-.4031	16	-.006	20	+.001

Figure 6.4 (cont'd)

Date 1964	Julian Date 2438000 +	t 1964	WASHINGTON Stars	O-A	RICHMOND Stars	O-A
Aug 7.3	614.8	-.4004	12	-.012	20	-.001
8		-.3976	--	---	--	---
9		-.3949	19	-.002	16	-.004
10		-.3921	10	+.007	--	---
11		-.3894	--	---	--	---
12	619.8	-.3867	--	---	--	---
13		.3839	19	-.004	20	-.010
14		-.3812		---	14	.000
15		-.3785		.013	--	---
16		-.3757		---	18	+.003
17	624.8	-.3730	--	---	20	-.002
18		-.3702	10	-.004	18	-.006
19		-.3675	9	+.001	20	-.026
20		-.3648	15	-.008	--	---
21		-.3620	--	---	--	---
22	629.8	-.3593	27	+.013	10	+.015
23		-.3566	25	+.007	16	+.003
24		-.3538	18	-.004	16	+.007
25		-.3511	--	---	17	-.006
26		-.3483	18	.000	--	---
27	634.8	-.3456	20	+.008	--	---
28		-.3429	25	+.007	--	---
29		-.3401	--	---	--	---
30		-.3374	--	---	19	-.008
31		-.3347	--	---	20	+.010
Sep 1	639.8	-.3319	--	---	15	+.011
2		-.3292	25	+.006	29	+.001
3		-.3264	19	+.001	18	+.002
4		-.3237	18	-.008	20	+.004
5		-.3210	11	-.006	21	-.005
6	644.8	-.3182	18	.000	5	.000
7		-.3155	17	-.002	20	.000
8		-.3127	23	+.006	27	.000
9		-.3100	27	-.005	20	-.007
10		-.3073	26	-.015	20	-.008
11	649.8	-.3045	--	---	19	+.022
12		-.3018	--	---	--	---
13		-.2991	--	---	--	---
14		-.2963	21	+.001	20	+.001
15		-.2936	28	-.006	10	+.012
16	654.8	-.2908	--	---	--	---
17		-.2881	25	.000	--	---
18		-.2854	6	+.001	6	-.001
19		-.2826	--	---	4	+.019
20		-.2799	--	---	--	---
21	659.8	-.2772	--	---	19	+.003
22		-.2744	24	+.003	-	---
23		-.2717	27	+.001	--	---
24		-.2689	16	-.006	15	-.008
25		-.2662	28	-.001	18	-.017
26	664.8	-.2635	26	-.007	8	+.009
27		-.2607	19	+.008	--	---
28		-.2580	--	---	19	.000
29		-.2553	--	---	10	-.013
30.3		-.2525	--	---	15	+.006

IV. TIMES OF EMISSION, A.1 - UT2C, AND DEVIATIONS IN FREQUENCY ON A.1.

10. The system of atomic time, A.1, is based on the operation of cesium standards of the Naval Observatory at Washington and Richmond, and about seven others located internationally. The assumed frequency of cesium is 9 192 631 770 cycles per second. The second is that defined by the International Committee of Weights and Measures in 1956 (see Time Service Notice No. 6).

11. A.1 - UT2C is the difference between a clock which indicates atomic time, A.1, and a clock synchronized with the emitted signal.

12. $\Delta F/F$ is the deviation in frequency of the carrier wave of the station with respect to the frequency of A.1. It is given by the formula:

$$\frac{\Delta F}{F} = \frac{\text{Carrier} - f(A.1)}{f(A.1)}$$

The unit is 1 part in 10^{10}.

Figure 6.4 (cont'd)

13. Values of A.1 - UT2C for intermediate dates may be obtained by interpolation, except as noted

A.1 - UT2C

1964		NBA	WWV
Jul	3	$3^s.1408$	$3^s.1390$
	13	3.1537	3.1519
	23	3.1667	3.1649
Aug	2	3.1797	3.1778
	12	3.1926	3.1907
	22 (3)*	3.2054	3.2036
Sep	1	3.3183	3.3166
	11	3.3313	3.3295
	21 (4)*	3.3443	3.3425
Oct	1	3.3582	3.3565

Monthly Values of ΔF/F

1964	NBA	WWV
Jul	-150.1	-149.8
Aug	-149.2	-149.6
Sep	-150.0	-150.0

Daily Values of ΔF/F for NBA

1964	Jul	Aug	Sep
1	-149.7	-149.9	-149.4
2	-150.9	-150.0	-149.1
3	-150.5	-150.3	-148.5
4	-150.0	-150.1	-149.2
5	-150.4	-149.1	-149.7
6	-150.2	-148.8	-149.5
7	-150.5	-148.9	-149.3
8	-149.8	-149.0	-150.0
9	-149.9	-149.1	-150.4
10	-149.8	-149.0	-150.3
11	-150.2	-149.2	-150.3
12	-150.0	-149.3	-150.8
13	-149.9	-149.2	-150.8
14	-150.2	-149.1	-150.7
15	-149.8	-149.4	-150.1
16	-150.0	-149.2	-150.5
17	-150.1	-148.8	-150.3
18	-150.0	-148.4	-150.5
19	-150.0	-149.3	-150.6
20	-150.2	-148.6	-150.3
21	-150.2	-149.3	-150.6
22	-150.4	-148.7	-150.7
23	-150.2	-149.2	-150.6
24	-150.2	-149.8	-150.7
25	-150.0	-149.6	-149.8
26	-150.0	-149.1	-149.6
27	-149.9	-149.4	-149.2
28	-150.0	-148.9	-149.4
29	-150.0	-149.1	-149.4
30	-150.3	-149.2	-149.3
31	-149.9	-149.1	
Mean	-150.1	-149.2	-150.0

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Superintendent

Figure 6.4 (cont'd)

It follows that

$$T^i = UTC + \Delta i. \tag{6.3}$$

The quantities Δi of a specific reduction are shown in Table 6.1 below.

Table 6.1

Δi values from Preliminary Emission Times No. 178 and Time Signals Bulletin No. 207.

Epoch: $3^h\ 23^m\ 14.2020$ UTC, August 19, 1964				Station: WWV
i	Δi_p	Δi_f	$\Delta i_f - \Delta i_p$	$T^i = UTC + \Delta i_f$
UT2	$-0^s.120$	$-0^s.1274$	$-0^s.0074$	$3^h\ 23^m\ 14^s.0746$
UT1	-0.105	-0.1132	-0.0082	14.0888
UT0 (W)	-0.119	-0.1262	-0.0072	14.0758
UT0 (R)		-0.1192	-0.0002	14.0828
A.1	+3.202	+3.1998	-0.0022	17.4018

Subscripts p and f refer to preliminary and final emission times, respectively; (W) and (R) refer to the USNO and Richmond, respectively.

Interpolation in the Bulletin is permissable, except where marked by an asterix, which designates that a step adjustment in phase has been made between tabulated dates. Interpolation between successive PET's could be made if no step adjustment has been made in the interval between two issues. The variation in the corrections is, however, so small that interpolation is unwarranted for approximate reductions.

Usually, astronomic longitudes are referred to the mean pole. The correction for the variation of the local meridian for an arbitrary station j, is given by Equation (4.15), which reads

$$\Delta\lambda_j^s = -\,1/15(x \sin\Lambda_j + y \cos\Lambda_j) \tan\Phi_j.$$

This correction has to be applied when longitudes are reduced to either UT1 or UT2. [Bomford, 1962, p. 307] prefers to reduce longitudes to UT1. The USC & GS apparently reduces longitudes to UTO without specifying however the reference, i.e., UTO (W), UTO (R) or UTO (local). It seems more logical to reduce to UT2 so that longitudes observed at different times and places may be directly comparable.

Should it be desirable, for some odd reason, to reduce an observed longitude to the instantaneous local meridian, a differential polar motion correction has to be applied.

The differential correction is equal to the difference between UTO^j at the local meridian and UTO^i at the meridian of the observatory to which UTO refers. By definition (6.2),

$$UT2 = UTO^j + \Delta\lambda^j + \Delta S, \tag{6.2a}$$

and

$$UT2 = UTO^i + \Delta\lambda^i + \Delta S, \tag{6.2b}$$

where superscripts j and i refer to an arbitrary observing station and arbitrary observatory, e.g., USNO or Richmond, and $\Delta\lambda$ and ΔS are as defined.

Subtracting (6.2b) from (6.2a) gives

$$UTO^j - UTO^i = (\Delta\lambda^i - \Delta\lambda^j). \tag{6.4}$$

The quantity $(\Delta\lambda^i - \Delta\lambda^j)$ is the differential correction that has to be applied to the observed longitude, given by

$$\delta\lambda^s = 1/15 \quad (x \sin\Lambda_j + y \cos\Lambda_j) \tan\Phi_j - (x \sin\Lambda_i + y \cos\Lambda_i) \tan\Phi_i \quad . \tag{6.5}$$

Compare (6.5) to (4.19).

Reduction to UTO^i using PET becomes more or less meaningless since UTO^i refers to an unspecified meridian somewhere between the USNO and Richmond [Markowitz, 1965].

The x and y in Equations (4.15) and (6.5) should be the interpolated coordinates of the instantaneous pole as furnished by the RLS (see Section 4.24). The PET also lists the provisional x and y coordinates which are identical to those listed in Table C of the RLS (see Figure 4.2).

It follows that final longitudes are given by

$$\begin{aligned} \Lambda_{UT2} &= \Lambda^{\circ} + \Delta t + \Delta UT2 + \Delta\lambda \\ \Lambda_{UT1} &= \Lambda^{\circ} + \Delta t + \Delta UT1 + \Delta\lambda \\ \Lambda_{UT0} &= \Lambda^{\circ} + \Delta t + \Delta UT0 + \delta\lambda, \end{aligned} \tag{6.6}$$

where Λ_{UT2}, Λ_{UT1}, and Λ_{UT0} are the final longitudes reduced to UT2, UT1, and UTC, respectively; Λ° is the mean observed longitude; Δt is the radio propagation delay; $\Delta UT2$, $\Delta UT1$, $\Delta UT0$ are the time corrections taken from a specific Time Service Bulletin; and $\Delta\lambda$, $\delta\lambda$ are the appropriate polar motion corrections.

In addition to the values UT2-UTC and A.1-UTC, which have been used in the foregoing example, the Bulletin also provides in part II the differences between the adopted UT2 and A.1. Part III lists the differences between observed UT2 (observed UT2 = UTO + $\Delta\lambda$ + ΔS) at Washington and Richmond and the adopted UT2, covering the period for which corrections are given. Part IV lists the differences A.1-UTC, monthly values of $\Delta F/F$ for NBA and WWV, and the daily values $\Delta F/F$ for NBA. It should be noted that the internationally adopted value, $\Delta F/F$ (frequency offset prescribed by the BIH), was $- 150 \times 10^{-10}$ during 1964.

6.511 Remarks about Time Signals Bulletins issued for periods prior to January 1, 1962

The conventional longitudes of time service stations have undergone changes between 1960 and 1962. The changes introduce a discontinuity in the adopted UT2 of the USNO.

[USNO, 1962a] lists the longitudes, and the corrections which have to be applied to adopted UT2 values prior to January 1, 1962 in order to reduce them to values corresponding to the new longitudes. The corrections have to be applied in full magnitude and proper sign if longitudes observed before and after January 1, 1962 are to be compared.

The longitudes and time corrections listed in Tables 6.2 and 6.3 respectively, are reproduced from the above publication.

Table 6.2

Conventional longitudes of time service stations

Effective Dates	to December 31, 1960	Jan. 1 to Dec. 31, 1961	Since Jan. 1, 1962
USNO	$-5^h\ 08^m\ 15^s.780$	$-5^h\ 08^m\ 15^s.740$	$-5^h\ 08^m\ 15^s.729$
Richmond	-5 21 31.759	-5 21 31.730	-5 21 31.719
Herstmonceux	+0 01 21.091	+0 01 21.091	+0 01 21.102

Table 6.3

Corrections to UT2 epochs obtained prior to January 1, 1962

Effective Dates	Corrections	Time Signals Bulletins
to Dec. 31, 1960	$-0^s.044$	through No. 194
Jan. 1 to Dec. 31, 1961	-0.011	Nos. 195 - 196
since Jan. 1, 1962	0	No. 197 and beyond

The form of the Bulletin was also changed beginning with Bulletin No. 195, January 1, 1961. Prior to this date two Bulletins were issued. Bulletin B gave preliminary, Bulletin A gave final times of reception of signals in terms of the adopted UT2.

To obtain final times of emission from these older Bulletins use

$$\text{UT2 (emitted)} = \text{UT2 (reception)} - \Delta t^\circ \qquad (6.7)$$

where UT2 (reception) is taken from the Bulletin (A or B), and Δt° is the propagation delay between the transmitting station and the USNO. (Assumed is again that propagation delay has been applied for the transmission between reception and transmission site.)

The tabulated quantities are of the form UT2 (reception) - UTC. For interpolation of ΔUT2 the rules given above are applicable.

6.52 Explanation and use of the Bulletin Horaire

The Bulletin Horaire is the official organ of the BIH, which has been mentioned already in Chapter IV. There, its publications in connection with polar motion and variation of rotation speed of the Earth were briefly described.

Now we will describe how time corrections to epochs of observations can be extracted from the Bull. Hor. The procedure is different from that described in Section 6.51, but similar results can be obtained. It should be kept in mind that the fictitious mean observatory replaces the USNO when the final corrections from the Bull. Hor. are used.

6.521 The formation of the mean observatory

The following description of the formation of the mean observatory is taken from [Stoyko, 1964a, pp. 2-5].

The mean observatory, or what amounts to the same, the final epoch of UT2, is determined from the times of emission of UTC signals based on observations for UT2 at about 45 time observatories (1964). The observatories are listed in Figure 6.7.

The times of emission are calculated taking into account the results of astronomical observations, the rate and setting errors of the observatory clocks, and the results of time signal and frequency monitoring by cooperating time services. Times of emission are calculated by correcting the times of reception for transmission delay according to the adopted propagation velocities given in Section 5.41, where specific reference to the BIH was made.

The calculation of the final UT2 is based on the following hypothesis:

(1) the total number of participating observatories remains constant throughout one year;

(2) all observatories have equal weight, with exception of those that have known inferior precision and get a weight of 0.5. The total weight for 1964 was 32;

(3) the algebraic mean of the systematic errors of the observatories used is equal to zero;

(4) the algebraic mean of errors in reception (monitoring) is equal to zero;

(5) polar motion and seasonal variation are applied to the observations in accordance with international agreements (see Chapter IV).

In principle, the calculation of the time corrections, referred to UT2 of the mean observatory, is as follows:

Let a,b,c, ... n, be a group of time services that receive a signal V emitted from one station. (V has a computed value of UT2.) Then,

$$h_a - t_a + r_a + p_a = h_b - t_b + r_b + p_b = \cdots = h_n - t_n + r_n + p_n = T, \qquad (6.8)$$

where h_a, h_b, $\cdots$, h_n, are the time of reception of the signal V at the n stations;

t_a, t_b, $\cdots$ t_n, are the propagation delays;

r_a, r_b, $\cdots$ r_n, are the accidental errors;

p_a, p_b, $\cdots$ p_n, are the systematic errors, e.g., error in conventional longitudes, clock errors, etc.; and

T is the UT2 time of emission of the signal V.

If one specific observatory is chosen as reference, then

$$h_i-h_a-(t_i-t_a) = (p_a-p_i) + (r_a-r_i), \tag{6.9}$$

where i = b,c,d, $\cdots$ n, and a refers to the reference observatory. The left side of Equation (6.9) is known and can be represented graphically by a smoothed curve. For a particular epoch, say 0^hUT, values R_i are extracted from the graph.

By replotting the values R_i, a curve is obtained which allows interpolation to $0^s.0001$ for the chosen epoch.

Now, let

$$R_i = p_a - p_i, \tag{6.10}$$

where i = a,b,c, $\cdots$n. Since, by hypothesis (3), $\sum p_i = 0$, we have

$$p_a = \sum R_i \;/n, \tag{6.11}$$

which represents a certain mean value which is adopted to represent the mean observatory. The individual differences $p_a - R_i = p_i$ are tabulated in the Bull. Hor. as UT2-UTC, for each participating station, UT2 referring now to the mean observatory.

If it is necessary to refer a time correction to another than the current mean observatory, corrections must be applied, which are a function of the number and quality of the participating observatories that comprised the mean observatory used in the past. In addition, corrections have to be applied for the different mean poles used in the past to calculate the polar motion correction.

The published corrections are given below in tabular form [Stoyko, 1964b].

Table 6.4

Corrections to UT2 for changes in the mean observatory

Year	$\Delta\lambda_o$	Year	$\Delta\lambda_o$	Year	$\Delta\lambda_o$	Year	$\Delta\lambda_o$
1931	$-0^{s}.0030$	1938	$-0^{s}.0022$	1945	$-0^{s}.0010$	1952	$-0^{s}.0049$
32	- 29	39	- 25	46	- 35	53	- 47
33	- 16	40	- 34	47	- 47	54	- 38
34	- 24	41	- 17	48	- 45	55	- 52
35	- 23	42	- 18	49	- 45	56	- 62
36	- 23	43	- 17	50	- 40	57	- 72
37	- 25	44	- 11	51	- 50	58	- 49

Table 6.5

Corrections to UT2 for changes in the mean pole of the epoch

Year	Δp	Year	Δp	Year	Δp	Year	Δp
1931	$+0^{s}.0025$	1940	$+0^{s}.0037$	1948	$+0^{s}.0067$	1956	$+0^{s}.0017$
32	+ 030	41	+ 017	49	+ 037	57	+ 025
33	+ 093	42	+ 005	50	+ 058	58	+ 002
34	+ 065	43	+ 004	51	+ 015	59	+ 044
35	+ 090	44	+ 002	52	+ 034	60	+ 044
36	+ 097	45	+ 021	53	+ 041	61	+ 044
37	+ 106	46	+ 028	54	+ 001	62	+ 0
38	+ 109	47	+ 028	55	+ 006	63	+ 0
39	- 118						

The corrections are applied when time, prior to January 1, 1962 has to be reduced to the system used since that date.

For the period 1931 to 1955, inclusive, the final UT2 time of emission in the present system is given by

$$UT2 = UT2 \text{ (old tabulation)} + \Delta p + \Delta\lambda_0 + \Delta S, \qquad (6.12)$$

where Δp is taken from Table 6.5, $\Delta\lambda_0$ from Table 6.4, and ΔS is the seasonal variation applicable to the epoch in question (see Section 4.31).

For the period after January 1, 1956, the corresponding formula is

$$UT2 = UT2 \text{ (old tabulation)} + \Delta p, \qquad (6.13)$$

where Δo is taken from Table 6.5.

Since January 1, 1962 the values given in the Bull. Hor., applicable to the epoch in question are used without correction. The manner in which the Bull. Hor. is used is described in the next section.

The mean observatory is defined to have 0° longitude. The fact that it also has a latitude which may be different from zero is usually not mentioned. If we solve Equation (4.9) for $\Lambda = 0°$, we find that the instantaneous latitude of the mean observatory is equal to the x component of the instantaneous pole, the mean latitude being zero. It follows that a correction to UT2 (mean observatory) arises because the assumption Φ(mean observatory) = 0° at the time of polar motion observation is not correct. However, the effect of polar motion on the mean observatory is constant for all observing stations and is absorbed in the terms z and d of Equations (4.10) and (4.16).

6.522 The use of the Bulletin Horaire pro er.

Recently, and very fortunately indeed, the form of the Bull. Hor. has been radically changed. The change was toward the better in this author's opinion. The first issue in the new form is Série J, No. 1. The new series covers periods after January 5, 1964, and is published bi-monthly. It contains all the information required for reduction of arbitrary epochs to UT0, UT1, UT2 or AT.

Prior to the change two series of the Bull. Hor. were in existence: a letter series, e.g., Série H, No. 6, which contained corrections to time signals to arrive at UT2 final, and a number series, e.g., Série 6, No. 10, which gave times of reception of signals from coordinated (and some non-coordinated) stations at the Paris Observatory. In addition, important information, e.g., coordinates of the pole, seasonal variation, definitions, etc., were contained in one or the other of the series.

For final time corrections the old letter series may be used in a manner similar to that described for the USNO Time Signals Bulletin in its present form; the old number series may be used as described in Section 6.511.

The new form of the Bull. Hor. combines both letter and number series. The last issues of the old series are those mentioned as examples above. A description of the contents of the new Bull. Hor. will follow. Specimen pages are included as Figures 6.5 through 6.10 for ease of understanding. A specific example of the reduction of an UTC epoch will be given later on.

Table 1, Figure 6.5: lists the differences $UT1-UT0^i = \Delta\lambda^i$, at 0^hUT for the tabulated dates. The values $\Delta\lambda^i$, tabulated for each observatory participating in the determination of the mean observatory, are identical to those listed in Table B of the RLS (see Figure 4.2).

Table 2, Figure 6.6: lists the differences UT2-UT1 = ΔS, at 0^hUT for the tabulated dates. Δ S is calculated from Equation (4.23). Table 2 appears only in the first issue of each year and is identical to Table A of the BIH (see Figure 4.5).

Table 3, Figure 6.7: lists the time services participating in the international program for the determination of UT2. Tabulated are the monthly systematic deviations UT2-UT2^i, i.e., the differences between UT2 final, adopted for the mean observatory, and UT2 determined at the individual observatories.

Table 4: provides information on transmission stations, e.g., schedules, frequencies, etc. The first issue of a year lists all coordinated stations and some non-coordinated stations. Table 4 of subsequent issues contains corrections and additions, if any.

Table 5: lists frequency offsets and step adjustments in phase that were, or have come, into effect during the period covered by the specific issue. Future offsets and step adjustments are also given at this place.

Table 6, Figure 6.8: lists the differences UT2-A3, at 0^hUT, for the tabulated dates. A3 is the atomic time adopted by the BIH, and is given by the mean of three caesium standards located at NBS, NPL, and LSRH. By definition UT2-A3 = $0^s\!.0000$, at 20^hUT, January 1, 1958 (see Section 1.2). Also given are the monthly mean systematic deviations A3-AT^i, where i stands for other atomic standards, e.g., NPL, NBS, etc. By definition (A3-AT^i) = $0^s\!.0000$ at 0^hUT, January 1, 1961.

Table 7, Figure 6.9: Part 1 lists the differences UT2-UTC and A3-UTC, at 0^hUT, for the tabulated dates. The values are mean values and pertain to the stations listed in Part 2 of Table 7. Part 2 lists the monthly mean differences (UTC-Signal) emitted = E, the quantity being used in the determination of definitive emission times of a particular station (see example).

It should be noted that UTC as used in the Bull. Hor. refers to a fictitious signal emission time of the mean observatory, and Signal stands for UTC of a specific station.

Table 8, Figure 6.10: lists the differences UT2-Signal for some coordinated stations that cannot be accomodated in Table 7, and non-coordinated stations, at the times indicated at the head of the respective columns.

Table 8 concludes the Bull. Hor. as far as final corrections are concerned. The final correction data is on white pages. Each issue covers two months, about 12-15 months in arrears.

Tables 9 through 12 are on pink pages. Table 9 gives observational results of the Paris Observatory. Tables 10, 11, and 12 give the same data as Tables 6, 7, and 8, with the difference that UT2 is replaced by UT2 Pa, i.e., UT2 final, pertaining to the mean observatory, is replaced by UT2 as determined by the Paris Observatory. Tables 11 and 12 give times of reception, whereas Tables 7 and 8 give times of emission. This pink section of the Bull. Hor. covers 2 month periods, about 6 months in arrears.

Using the mean epoch of the sample reduction of Section 6.51, we find from Tables 1 through 7 of the Bull. Hor. Série J, No. 4 (Figures 6.5 through 6.9) the corrections Δi_m listed in Table 6.6 below. The notation is the same as in Section 6.51.

1. TU1-TU0 à 0^hTU (en 0^s0001)

Date 1964	J.J. 2438	x	y	Al	BA	BG	Bl	Bo	Bs	Bu
juil. 3	579,5	+0"170	+0"174	- 91	- 25	-194	-147	-187	-138	-151
13	589,5	+ 196	+ 150	- 80	- 41	-183	-139	-173	-122	-144
23	599,5	+ 219	+ 113	- 67	- 56	-167	-127	-157	-105	-135
août 2	609,5	+ 238	+ 93	- 52	- 71	-150	-113	-137	- 85	-123
12	619,5	+ 252	+ 59	- 36	- 85	-126	- 95	-112	- 61	-107
22	629,5	+ 260	+ 23	- 18	- 96	-100	- 75	- 84	- 36	- 88
sept. 1	639,5	+ 261	- 14	0	-106	- 70	- 52	- 54	- 10	- 67

Date 1964	G	H	HP	Ir	Kh	L	LP	M	Mi	MP	MS
juil. 3	-143	-181	-122	-105	-191	-272	- 24	-237	-135	- 27	- 29
13	-124	-164	-108	-132	-188	-263	- 40	-234	-122	- 41	- 13
23	-102	-144	- 93	-157	-182	-249	- 56	-226	-100	55	+ 3
août 2	- 77	-120	- 75	-179	-172	-230	- 71	-204	- 88	- 68	+ 20
12	- 50	- 92	- 54	-198	-156	-205	- 85	-196	- 67	- 80	+ 37
22	- 20	- 60	- 31	-212	-137	-174	- 97	-173	- 43	- 91	+ 54
sept. 1	+ 10	28	- 8	-221	-114	-138	-106	-145	- 19	- 98	+ 69

Date 1964	Mz	N	Nk	Nm	O	Pe	Pr	Pt	Pu	Q	Rc
juil. 3	+ 16	-138	-167	-181	+ 82	-138	-168	-180	-272	0	+ 44
13	- 3	-124	-163	-203	+103	-120	-155	-165	-263	0	+ 54
23	- 23	-106	-156	-222	+123	-100	-138	-147	-249	0	+ 63
août 2	- 42	- 87	-145	-236	+140	- 78	-119	-125	-230	0	+ 70
12	- 61	- 64	-130	-245	+155	- 53	- 95	- 99	-205	0	+ 76
22	- 79	- 39	-112	-249	+166	- 26	- 69	- 70	-174	0	+ 81
sept 1	- 95	- 13	- 90	-245	+173	+ 3	- 41	- 39	-138	0	+ 83

Date 1964	Rg	RJ	SC	SF	Ta	To	U	VJ	W	Zi
juil. 3	-234	+ 3	- 46	- 76	-129	+ 10	-152	-191	+ 68	- 22
13	-222	- 7	- 60	- 63	-138	- 6	-134	-180	+ 85	- 36
23	-207	- 17	- 73	- 49	-145	- 23	-114	-165	+100	- 49
août 2	-187	- 27	- 86	- 33	-150	- 40	- 91	-147	+114	- 62
12	-161	- 36	- 97	- 16	-150	- 57	- 64	-124	+125	- 74
22	-130	- 45	-105	+ 2	-147	- 72	- 35	- 98	+134	- 85
sept. 1	- 96	- 53	-111	+ 21	-140	- 86	- 5	- 69	+139	- 93

2. TU2-TU1

Voir Bulletin Horaire, n° 1, série J.

Figure 6.5: Values UT1 - UT0 at 0^hUT (unit 0^s0001)
J.J. = Julian Date, for abbreviations see Figure 6.7.

2. TU2 – TU1 à 0h TU (en 0^s0001)

Date 1964	J.J. 2438	TU2 – TU1
Jan. 5	399.5	– 45*
10	404.5	– 37
15	409.5	– 31
20	414.5	– 25
25	419.5	– 19
30	424.5	– 14
Fév. 4	429.5	– 8
9	434.5	– 1
14	439.5	+ 7
19	444.5	+ 15
24	449.5	+ 25
29	454.5	+ 37
Mars 5	459.5	+ 50
10	464.5	+ 64
15	469.5	+ 80
20	474.5	+ 98
25	479.5	+117
30	484.5	+137
Avril 4	489.5	+157
9	494.5	+178
14	499.5	+199
19	504.5	+219
24	509.5	+238
29	514.5	+255
Mai 4	519.5	+270
9	524.5	+284
14	529.5	+294
19	534.5	+301
24	539.5	+305
29	544.5	+304
Juin 3	549.5	+300
8	554.5	+291
13	559.5	+278
18	564.5	+262
23	569.5	+241
28	574.5	+216
Juil. 3	579.5	+189
8	584.5	+158
13	589.5	+125
18	594.5	+ 90
Juil. 23	599.5	+ 34
28	604.5	+ 16
Août 2	609.5	– 21
7	614.5	– 57
12	619.5	– 92
17	624.5	–126
22	629.5	–159
27	634.5	–187
Sept 1	639.5	–213
6	644.5	–235
11	649.5	–254
16	654.5	–269
21	659.5	–279
26	664.5	–287
Oct. 1	669.5	–290
6	674.5	–288
11	679.5	–284
16	684.5	–276
21	689.5	–267
26	694.5	–254
31	699.5	–240
Nov. 5	704.5	–223
10	709.5	–206
15	714.5	–188
20	719.5	–170
25	724.5	–152
30	729.5	–135
Déc. 5	734.5	–119
10	739.5	–104
15	744.5	– 89
20	749.5	– 76
25	754.5	– 65
30	759.5	– 55
35	764.5	– 46

* Les valeurs de la circulaire 91 bis et du tableau A du Bulletin Horaire n° 3, série 6, p.59 étaient établies pour 20h TU.

Table 6.6: Values ΔS = UT2 - UT1 at 0^hUT (unit 0^s0001)

3. SERVICES HORAIRES participant à la formation de l'heure définitive et moyennes mensuelles de l'écart systématique Pi = TU2 déf -TU2 i.

Observatoire	Abrn	Longitude	Latitude 1964	TU2 déf - TU2i Juillet (unité 0,0001 s)	Août
ALGER (BOUZAREAH)	Al	$-0^h 12^m 8^s,463$	+36°48',1	- 56	-131
BUENOS-AIRES Géog.	BAg	+3 54 4,471	-34 34,4	+ 58	+ 39
BUENOS-AIRES Nav.	BAn	+3 53 25,194	-34 37,3	-203	- 50
BOROWA GORA	BG	-1 24 8,947	+52 28,6	+273	+302
BELGRADE	Bl	-1 22 3,174	+44 48,2	+436	+452
BESANCON	Bs	-0 23 57,025	+47 14,9	+ 73	+ 53
BOROWIEC	Bo	-1 8 18,437	+52 16,6	-161	+ 79
BUCAREST	Bu	-1 44 23,115	+44 24,8	+103	- 13
GREENWICH (1)	G	-0 1 21,102	+50 52,3	+ 4	+ 23
HAMBOURG Hydrogr.	H	-0 40 3,679	+53 35,8	+ 57	+ 66
HAUTE PROVENCE (2)	HP	-0 22 52,009	+43 55,9	+116	+162
IRKOUTSK Astr.	Ira	-6 57 22,748	+52 16,7	- 10	+ 93
IRKOUTSK Mes.	Irm	-6 57 11,843	+52 16,4	- 18	- 22
KHARKOV	Kh	-2 24 55,838	+50 0,0		"
LENINGRAD Astr.	La	-2 1 10,800	+59 56,5	+159	+195
LENINGRAD Mes.	Lm	-2 1 15,930	+59 55,1	+353	+241
LA PLATA	LP	+3 51 43,639	-34 54,5	- 44	- 95
MOSCOU Astr.	Ma	-2 30 10,695	+55 42,0	- 58	- 74
MOSCOU Mes.	Mm	-2 28 55,597	+55 58,7	- 21	- 97
MILAN	Mi	-0 36 45 ,31	+45 28,0	-165	-102
MONT-POURPRE	MP	-7 55 17,027	+32 4,0	+ 9	+ 44
MONT-STROMLO	MS	-9 56 1,406	-35 19,3	+ 35	+ 45
MIZUSAWA	Mz	-9 24 31,406	+39 8,1	+ 50	+ 40
NEUCHATEL	N	-0 27 49,779	+46 59,8	-150	-180
NIKOLAIEV	Nk	-2 7 53,817	+46 58,3	-513	-518
NOVOSSIBIRSK Mes.	Nm	-5 31 38,193	+55 2	-123	-112
OTTAWA	O	+5 2 51,940	+45 23,6	+ 55	+ 34
PARIS	Pa	-0 9 20,921	+48 50,2	- 82	- 97
PRAGUE (3)	Pr	-0 57 34,886	+50 4,6	+ 9	- 26
POTSDAM Géod.	Pt	-0 52 16,069	52 22,9	+134	+ 87
POULKOVO	Pu	-2 1 18,572	+59 46,3	-167	-230
QUITO	Q	+5 13 59,734	-00 14,0	+ 18	+ 23
RICHMOND	Rc	+5 21 31,719	+25 36,8	- 5	+ 2
RIGA	Rg	-1 36 27,716	+56 57,1	- 87	-238
RIO-de-JANEIRO	RJ	+2 52 53,467	-22 53,7	-112	- 68
SANTIAGO-du-CHILI	SC	+4 42 11,700	-33 23,8	+720	+628
SAN-FERNANDO	SF	+0 24 49,241	+36 27,7	+478	+490
TACHKENT	Ta	-4 37 10,488	+41 19,5	-116	- 3
TOKYO (Mitaka)	To	-9 18 9,930	+35 40,3	- 44	- 46
UCCLE	U	-0 17 25,937	+50 47,9	-112	- 99
U. R. S. S.	Ur	Obser. moyen		- 13	- 19
VARSOVIE-JOZEFOSLAV	VJ	-1 24 8,600	+52 5,9	+ 2	-654 (4)
WASHINGTON	W	+5 8 15,729	+38 55,3	+ 32	+ 33
ZI-KA-WEI	Zi	-8 5 42,864	+31 11,5	+109	+ 98

(1): L'observatoire se trouve à HERTSMONCEUX.-(2): L'observatoire se trouve à SAINT-MICHEL.-(3): Les observations astronomiques ont été faites à PRAGUE et PECNY (λ = $-0^h 59^m 9^s,363$; φ = + 49°54'56"). (4) Saut de 100 ms du 31 août au 1er septembre (-976 le 31 août, -33 le 1er sept.).

Figure 6.7: Observatories participating in the formation of the mean observatory (Λ is positive to the west) and values UT2 - UT2^i (see text).

5. SAUTS ET REAJUSTEMENTS

Pas de sauts, ni réajustements signalés depuis le précédent Bulletin Horaire. Le décalage de fréquence pour le Temps Coordonné est fixé à -300.10^{-10} à partir du 1er janvier 1966.

6. TEMPS ATOMIQUE

A3 est le temps atomique donné par la moyenne des étalons suivants :

Boulder (Bld),
Teddington (ET),
Neuchâtel (N).

Origine : TU2 déf - A3 = $00^s.0000$, le 1er janvier 1958 à 20^hTU.

Date	J. J. 2438	TU2 déf - A3 à 0^hTU
1964 juill. 3	579.5	$-3^s.2025$
8	584.5	2108
13	589.5	2199
18	594.5	2293
23	599.5	2385
28	604.5	2481
août 2	609.5	2576
7	614.5	2670
12	619.5	2764
17	624.5	2858
22	629.5	2951
27	634.5	3043
sept. 1	639.5	3147

Ecarts des temps atomiques individuels : A3 - TAi. On rappelle que les divers TAi ont été remis en coïncidence le 1er janvier 1961.

	Etalon i		A3 -TAi en $0^s.0001$ (juill.et août 1964)	Origine
A3	Boulder	Bld	- 5	1er janvier 1961
	Teddington	ET	+ 29	"
	Neuchâtel	N	- 25	"
	Bagneux	Bgn	+173	"
	Washington (Lab.Nav.)	WL	+ 65	"
	Washington (Obs.Nav.)	WNO	+127	"
	Richmond (Fl.)	RNO	+ 18	"
	Moyenne générale	AM	+ 55	

Figure 6.8: Values UT2 - A3 and A3 - AT^i. (see text)

7 - TEMPS COORDONNE

Heure définitive de l'émission des signaux horaires coordonnés. L'observatoire moyen a le poids 32 (voir fascicule J2).

1°) Temps coordonné

Date		J.J. 2438	TU2 déf - TUC à 0^hTU (en $0^s{,}0001$)	A3-TUC à 0^hTU	Notes
1964 juill.	3	579,5	9014	$3^s{,}1039$	(1) TUC a été
	8	584,5	8995	1103	retardé de
	13	589,5	8968	1167	100ms le 1er
	18	594,5	8938	1231	sept. 1964 à
	23	599,5	8910	1295	0^hTU.
	28	604,5	8878	1359	
août	2	609,5	8847	1423	
	7	614,5	8817	1487	
	12	619,5	8787	1551	
	17	624,5	8757	1615	
	22	629,5	8729	1679	
	27	634,5	8700 (1)	1743 (1)	
sept.	1	639,5	9660	2807	

2°) Ecarts individuels E : E = (TUC - signal) émis

Signal	fréquence en kHz	E en $0^s{,}0001$ juillet	août	Notes
CHU	toutes fr.	0	+ 6	(1) • indique que le calcul de
FTA91•(1)	91,15	+63	+66	(TU2déf - Signal) émis, à une
FTH42•(2)	7428	+10	+14	date quelconque, par l'inter-
HBB•	96,05	- 4	- 2	polation du tableau 7, n'intro-
HBN•	5000	-16	-12	duit pas d'erreur supérieure à
				$0^s{,}0003$. Pour les autres signaux,
IAM	5000	+33	(3)	cette erreur est comprise entre
IBF	5000	+20	+26	$0^s{,}0004$ et $0^s{,}0010$ (sauf NPM).
JAS22•	16170	-27	-25	
JJY	toutes fr.	- 1	- 1	(2) et autres signaux de Pontoise
LOL	toutes fr.	+ 6	+ 6	FTK77 et FTN87.
MSF•(4)	toutes fr.	+24	+24	(3) 2 août : +22
NBA	24	-32	-30	7 août : +16
NBA	autres fr.	+ 8	+ 9	12 août : + 4
NPG	toutes fr.	-29	-36	17 août : -23
NPM	toutes fr.	+22	+33	22 août : -43
				27 août : +43
NSS	toutes fr.	- 2	- 2	(saut de +100 environ entre le
OLB5/OLD2•	3170; 18985	+30	+41	24 et le 25 août).
OMA•	50	+27	+32	
OMA•	2500	+11	+25	(4) et signaux associés : GBR,
WWV•	toutes fr.	- 5	- 2	GPB30B, GIC27, GIC33, GIC37.
WWVH•	toutes fr.	- 6	- 2	
ZUO	toutes fr.	- 5	- 4	

Figure 6.9: Values UT2 - UTC and E (see text).

8. TU2 déf - Signal, pour les signaux non coordonnés et certains signaux coordonnés ne figurant pas au tableau 7.

Août 1964	RES 100(1) 0^h0^m (2)	RBT t.fr. 0^h0^m	DAN 2614 0^h0^m	DAM (3) 0^h0^m	VHP2* 4286 0^h30^m	VHP3* 6428 0^h30^m	VHP4* 8478 0^h30^m	VHP5* 12907 0^h30^m	VHP6* 17257 0^h30^m	VHP7* 22485 0^h30^m	PPE* 8720 0^h30^m	XSG t.fr. 3^h6^m
1	0043	0048	0183	0025	8892	8837	8866	8875	8869	8867	8842	0003
2	0038	0043	0188	0027	8885	8854	8859	8869	8859	8858	8830	9998
3	0035	0040	0190	0026	8872	8850	8850	8862	8852	8851	8831	9994
4	0033	0038	0186	0024	8878	8845	8844	8856	8848	8846	8810	9991
5	0034	0038	0185	0023	8874	8835	8836	8851	8842	8841	8857	9987
6	0035	0038	0177	0024	8875	"	8836	8845	8835	8834	8876	9979
7	0034	0036	0174	0025	8866	"	8823	8838	8829	8829	8872	9973
8	0034	0037	0174	0026	8824	"	8817	8828	8823	8821	8861	9967
9	0033	0036	0174	0026	8818	8836	8810	8823	8818	8813	8815	9958
10	0029	0034	0176	0027	8810	8830	8802	8816	8809	8808	8865	9953
11	0026	0031	0175	0029	8804	8825	8798	8811	8806	8801	8766	9947
12	0023	0027	0178	0032	8809	8828	8801	8814	8808	8803	8777	9942
13	0021	0027	0179	0036	8799	8797	8798	8804	"	"	8777	9934
14	0020	0027	0184	0037	8787	8798	8786	8794	8786	8785	8812	9927
15	0019	0027	0185	0038	8778	8790	8776	8784	8779	8778	"	9922
16	0016	0022	0187	0039	8768	8783	8768	8780	8771	8769	"	9915
17	0013	0016	0186	0040	8762	8777	8762	8771	8765	8764	8753	9913
18	0012	0016	0188	0040	8752	8768	8752	8761	8754	8752	"	9916
19	0009	0014	0191	0042	8743	8769	8746	8752	8746	8745	8742	9914
20	0005	0010	0194	0041	8740	8765	8739	8751	8742	8741	8744	9893
21	0003	0007	0194	0042	8740	8761	8736	8746	8739	8740	8717	9893
22	0002	0007	0192	0041	8734	8758	8730	8748	"	"	8787	9892
23	0001	0007	0193	0041	8733	8758	8727	8748	8732	8727	8710	9887
24	0001	0006	0194	0042	8725	8763	8722	8747	8725	8724	8705	9878
25	9999	0005	0196	0040	8720	8750	8717	8738	8724	8725	8727	9873
26	9998	0004	0198	0041	8713	8745	8711	8733	8715	8715	"	9870
27	9995	0002	0200	0042	8701	8733	8699	8717	8715	8701	8757	9864
28	9992	0000	0205	0044	8694	8694	8691	8709	8711	8695	8691	9858
29	9988	9996	0204	0041	8689	8723	8687	8706	8706	8689	8692	9851
30	9988	9993	0200	0040	8685	8701	8682	8699	8700	8684	"	9845
31	9987	9990	0194	0041	8676	8694	8674	8693	8694	8678	8691	9839

* Signaux coordonnés.

(1) fréquences en kHz.

(2) ainsi que RWM (toutes fréquences).

(3) 6475 et 12763 kHz.

Figure 6.10: Values UT2 - Signal at indicated hours (see text).

Table 6.6

Δi_m values from Bulletin Horaire, Serie J, No. 4

Epoch: $3^h\ 23^m\ 14^s.2020$ UTC, August 19, 1964				
i	* Δi_m	Table reference, equations	* $\Delta i_m - \Delta i_f$	T^i = UTC (WWV) + Δi_m
UT2	$-0^s.1257$	ΔUT2 = (UT2-UTC) + E; Table 7	$+0^s.0017$	$3^h\ 23^m\ 14^s.0763$
UT1	-0.1118	ΔUT1 = ΔUT2 - ΔS; ΔS from Table 2	+0.0014	14.0902
UT0(W)	-0.1258	ΔUT0(W) = ΔUT1-$\Delta\lambda$(W); $\Delta\lambda$(W) from Table 1	+0.0004	14.0762
UT0(R)	-0.1198	ΔUT0(R) = ΔUT1-$\Delta\lambda$(R), $\Delta\lambda$ (R) from Table 1	-0.0006	14.0822
A.1	+3.1991	ΔA.1 = ΔA3 + $0^s.035$	-0.0007	17.4011
A3	+3.1641	ΔA3 = ΔUT2 + (UT2-A3), Table 6		17.3661

*subscript m refers to mean observatory; Δi_f is taken from Table 6.1

Consulting Table 3, Figure 6.7, one finds the difference UT2-UT2(W) = $+0^s.0033$, and UT2 - UT2(R) = $+0^s.0002$. Assigning weight 1 to Washington and weight 2 to Richmond and meaning gives $+0^s.0018$ versus $\Delta UT2_m - \Delta UT2_f = +0^s.0017$.

A.1 cannot be determined directly from the Bull. Hor., owing to the difference in the initial epoch between A3 and A.1 (A3-A.1 = $-0\overset{s}{.}035$).

The corrections for polar motion that have to be applied to observed astronomic longitudes have been given in Section 6.51.

VII. SUMMARY

It has been shown how precise time is determined at observatories and how this time is disseminated through radio broadcasts.

The discussion necessitated excursions into several non-geodetic fields. For this reason a survey of the state of the art could be made only. The reader who is interested in specific details or theoretical foundations of the material covered is referred to the selected bibliography. Many of the entries contain extensive bibliographies themselves which may lead to further understanding.

To the geodesist it is of importance to realize that the epoch of UT2 and the interval of AT can be obtained with high accuracy when suitable equipment is employed for keeping and controlling local time.

Further, it is of significance that AT may be used in lieu of ET, owing to the fact that the correspondence between these two systems has been established.

The interaction between the many aspects of time determination and distribution may be best shown by the flow-chart-like diagram of Figure 7.1.

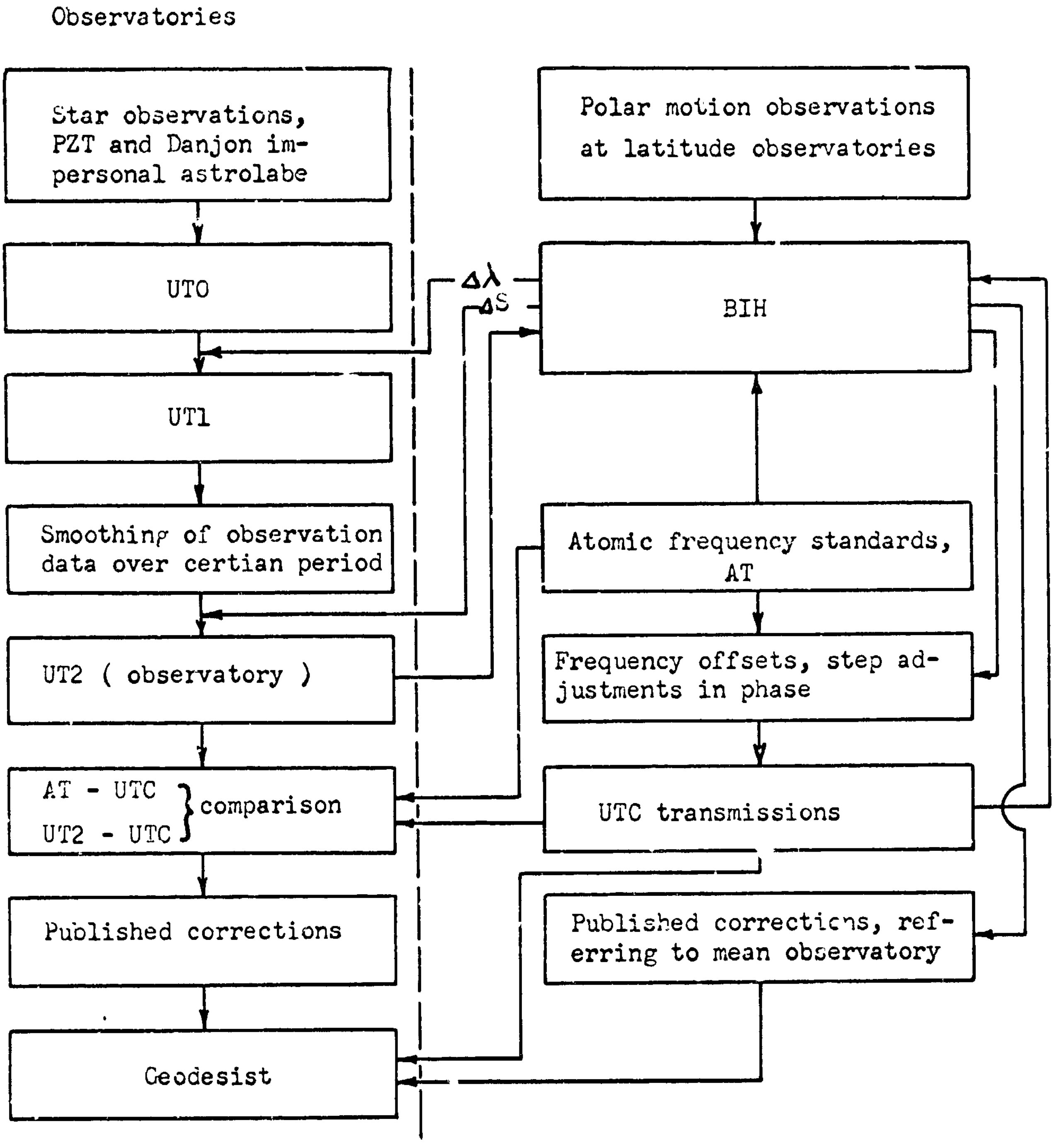

Figure 7.1: Chart showing the different aspects of time determination and time distribution.

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The following is an alphabetical list of the abbreviations used in the bibliography.

AJ	The Astronomical Journal
BIH	Bureau International de l'Heure
Bull. Hor.	Bulletin Horaire
IEEE	Institute of Electrical and Electronics Engineers
IRE	Institute of Radio Engineers
JR	Journal of Research
NBS	U. S. National Bureau of Standards
PICC	Proceedings of the International Conference on Chronometry
SAO	Smithsonian Institution Astrophysical Observatory
SREATS	Symposium on the Rotation of the Earth and Atomic Time
USC & GS	U. S. Coast and Geodetic Survey
USNO	U. S. Naval Observatory

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For the Department of Geodetic Science

Project Superviser Ivan I. Mueller Date 3.29.1966

For The Ohio State University Research Foundation

Executive Director Robert C. Stephenson RS Date 3/31/66